Energy Storage Grid Benefits Report

February 2026

Executive summary

Energy storage has the potential to provide a wide range of benefits to the electricity grid in Ireland. In this study we have primarily focused on the ability of storage to mitigate dispatch down in a future scenario characterised by high volumes of renewable energy generation.

For clarity, dispatch down refers to the following:

- **Constraint** denotes wind and solar power reduction due to transmission network thermal overloading (congestion).
- **Curtailment** denotes wind and solar power reduction due to system-wide operational limits such as the SNSP[1] threshold.
- **Surplus** (also known as oversupply) denotes wind and solar power reduction due to generation demand balance requirements.

Study approach

We have modelled a 2035 baseline grid scenario using EirGrid's median demand forecast with total demand of approximately 50 TWh and peak demand of 8 GW. Onshore wind was assumed to be 9 GW, solar was assumed to be 8 GW and offshore wind 5 GW.

The majority of grid reinforcement projects in EirGrid and SONI's Shaping our Electricity Future v1.1 roadmap are assumed to be place in our grid model. Our baseline grid scenario assumed no additional energy storage other than what is already operational with existing storage assets modelled as providing system services only.

Surplus is the dominant characteristic of our baseline scenario working out at approximately 25% dispatch down of renewable generation or 11 TWh. Surplus averages approximately 1 GW per hour with some individual hours experiencing up to 8-10 GW of surplus.

Curtailment is negligible in our model as we have assumed that system services and operational constraints are removed by 2035 with provision by low carbon inertia sources, battery storage and grid reinforcements.

Renewable dispatch down due to constraint reached approximately 5% for the system in total although the relative magnitude of constraint varies by location with regions such as the north-west, the mid-east (including the Dublin metro area), the south-west and the south-east experiencing the highest constraints.

To analyse the potential impacts of energy storage on mitigating dispatch down we selected 18 nodes throughout the grid where renewable constraint was highest as candidate locations for energy storage. These nodes were categorised into four main zones - the north-west, the mid-east, the south-east and the south-west. The focus on storage candidate locations was assumed to be outside the Dublin metro region, where approximately half the constraint level was identified. We assumed land constraints in the Dublin region could restrict development of storage units of the scale examined in this study.

For each of the 18 nodes we modelled 100 MW of energy storage of different durations ranging from 4-hour, 8-hour, 16-hour, 24-hour and 100-hour. Therefore, 1.8 GW of additional energy storage was assumed on the grid with each storage duration portfolio modelled separately and analysed individually.

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[1] System Non-Synchronous Penetration

Our modelling was undertaken in two phases:

- The first (Approach A) uses energy storage technologies only for constraint reduction, whereas
- The second (Approach B) uses energy storage technologies to mitigate the reduction of surplus, curtailment and constraint.

Key findings

Under Approach A, the total constraint due to onshore wind and solar technologies in our baseline scenario is appropriately 2 TWh. The addition of energy storage at these constrained nodes helps to reduce this constraint by 30 – 50% with the longest duration energy storage options having the most impact.

However, our analysis did show that the utility of lower duration energy storage options tends to max out sooner than the higher-duration equivalent. For instance, the 4-hour options are unavailable for more than 15% of the time when needed while the 100-hour options are unavailable less than 5% of the time. Hence our assessment of longer duration options is a conservative assessment of their ultimate capability – and showed that they have the capacity to deliver other services, for example to mitigate the high levels of surplus.

Under Approach B, energy storage helps to lower the volume of surplus with the longest durations resulting in a greater than 3 TWh reduction in surplus.

We also examined the impact of our energy storage portfolio on the output of fossil fuel generation. In our baseline grid model, fossil fuel generation makes up nearly 7.4 TWh of annual energy demand. All the different energy storage portfolios assessed reduce the need for fossil fuel generation – with the 8-hour energy storage portfolio reducing Ireland’s fossil fuel dependence by 1 TWh and the 100-hour energy storage option reducing Ireland’s fossil fuel dependence by over 2 TWh (i.e., nearly 30%). We found that while the shorter durations of energy storage result in less reductions in renewable surplus, their higher round trip efficiencies result in more fossil fuel generation displaced per unit of energy stored.

An important outcome of our analysis is that, while energy storage helps to reduce surplus, constraint in areas of the transmission network can increase, although at a much lower level than the overall surplus reduction. This can occur at the locations where the energy storage connections have been assumed, but more so where large-scale offshore is located as more renewable energy is released to flow through the grid. So, even though energy storage minimises overall dispatch down, which is a net positive, by releasing more renewable generation it can increase loading on the grid in certain scenarios and locations. Hence, adequate grid capacity must be a requirement to maximise the impact of a large level of long-duration energy storage

It is also important to note that we have not carried out a complete analysis of the economic benefits of energy storage. Rather the purpose of the study is to show the potential benefits that energy storage could have in alleviating transmission network congestion, reducing renewable generation dispatch down and moving towards a more decarbonised power system. More energy storage, in addition to what we studied, could be used to mitigate renewable dispatch down even further but our portfolio of 1.8 GW of energy storage with 100 MW of different durations at each of the 18 identified nodes is only intended to be illustrative and the actual development of energy storage will be dependent on market conditions, technology availability and investment signals.

Finally, the focus of this study has been primarily dispatch down but there are a wide range of additional services that energy storage can provide to the grid, several of which we have commented on in this report. This is not intended to be a completely exhaustive study, rather it illustrates that energy storage can provide a range of significant benefits to the future power system.

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1 Introduction

Ireland has seen rapid growth in energy storage with over 1 GW now connected to the electricity system. This figure includes 756 MW of battery storage projects and 292 MW from the Turlough Hill pumped storage power station.[2]

The battery storage projects have developed since 2020 with a focus on providing system services under EirGrid's DS3 volume-capped and volume-uncapped procurement framework. To date, battery storage systems in Ireland have been designed primarily to provide fast-acting reserve services to help manage system frequency events. These batteries tend to have an average duration of discharge of around 1 hour but can provide large amounts of power in millisecond timeframes to contain frequency deviations on the power grid.

As the energy storage market has matured and new storage technologies and capabilities are now in development there is increasing focus on the ability of longer duration energy storage to provide congestion services which can help alleviate renewable constraints, facilitate operation of the system, displace fossil fuel generation and defer or reduce the need for new transmission infrastructure.

In our grid study we have modelled the future transmission network in Ireland to explore the benefit of energy storage throughout the power system. We assume the power system is characterised by operational practices required in a net zero environment. For example, all operational constraints are relaxed and voltage and frequency regulation solutions are in place.

The focus of our grid study is primarily on constraint – but because high volumes of surplus are such a dominant characteristic of our future power system scenario, and ends up reducing constraint, the performance of our energy storage portfolio is inevitably more influenced by surplus rather than constraint. As such we have also quantified the impact of the assumed energy storage portfolios on mitigating surplus as well as constraint.

It is also important to note that we have not carried out any economic analysis on the storage assumptions underpinning our studies and our model does not simulate real-world market conditions in terms of price signals and economic dispatch. Rather the purpose of the study is to show the potential benefits that energy storage could have in alleviating transmission network congestion, reducing renewable generation dispatch down and moving towards a more decarbonised power system. Therefore, our portfolio of 1.8 GW of energy storage with 100 MW of different durations at each of the 18 identified nodes is only intended to be illustrative and the actual development of energy storage will be dependent on market conditions, technology availability and investment signals.

There are a wide range of services that energy storage can provide to the grid, several of which we have commented on in this report. This is not intended to be a completely exhaustive study, rather it illustrates that energy storage can provide a range of significant benefits to the future power system.

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[2] https://www.oireachtas.ie/en/debates/question/2025-09-08/193/#pq_193

2 Modelling methodology

TNEI has developed two bespoke approaches to deliver a grid-focussed energy storage study for ESI:

- The first (Approach A) uses energy storage technologies only for constraint reduction, whereas
- The second (Approach B) uses energy storage technologies to mitigate the reduction of surplus, curtailment and constraint.

Figures 1 and Figure 2 describes what the general methodologies look like. This section outlines the details underpinning the main elements of the approach. The study consists of the following main six phases:

- Scenario design,
- Operating schedule development,
- Grid model building,
- A base case grid simulation without energy storage (system needs analysis[3] and constraints analysis[4]),
- A screening study to identify energy storage locations, and
- Grid simulations to identify the benefits of energy storage.

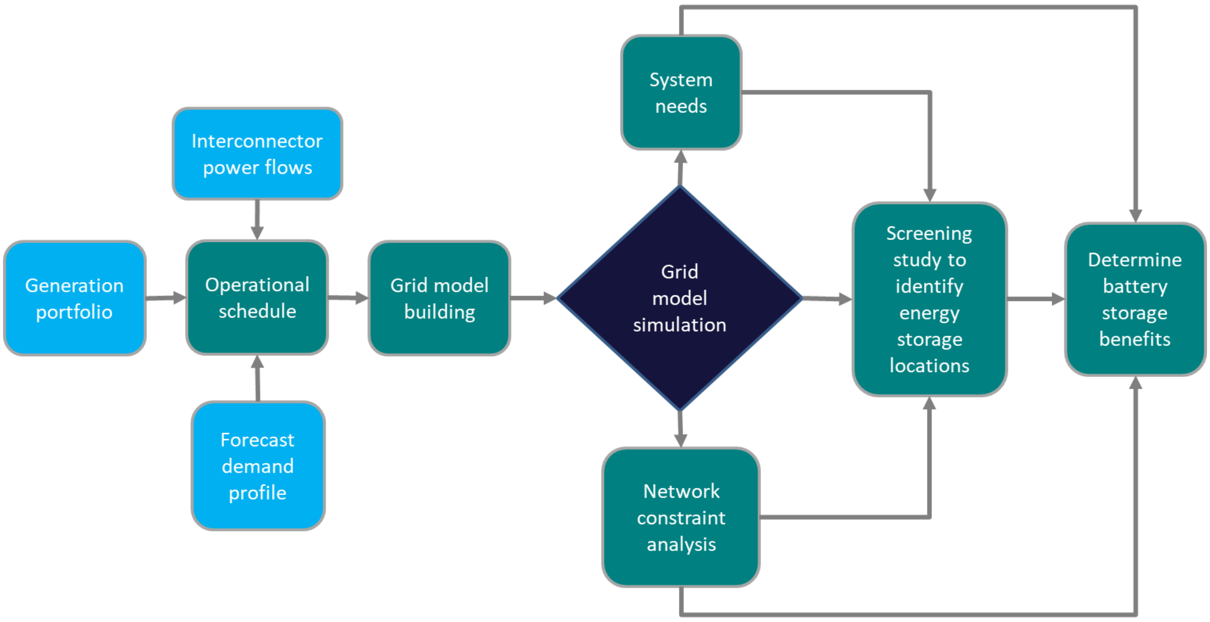

Figure 1 - High-level overview of our energy storage grid study Approach A

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[3] Needs analysis refers to the identification of thermal overloads on circuits and voltage violations at stations following N and N-1 performance tests.

[4] Constraints analysis refers to the identification of dispatch-down for renewable generation to ensure the transmission network is operated within standards.

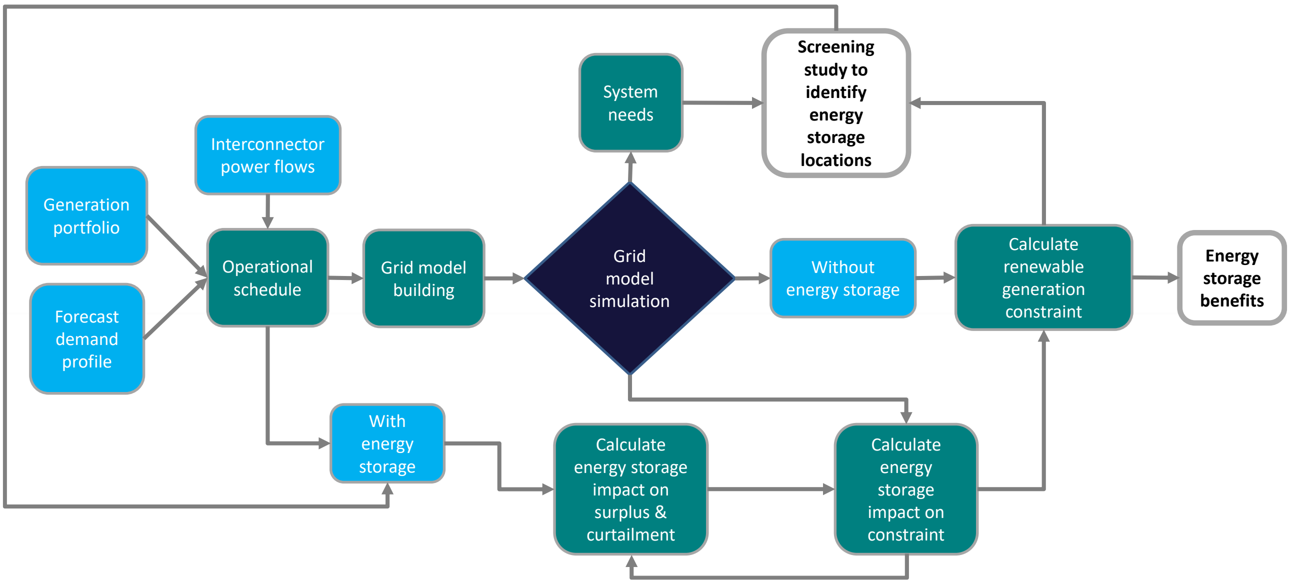

Figure 2 - High-level overview of our energy storage grid study Approach B

Phases 1 to 4 involve the simulation[5] of how the future power system behaves, identifying the following:

- system needs (overloaded circuits) using an unconstrained analysis; and
- what generation needs to be dispatched down to keep the system within thermal loading limits using a fully constrained analysis.

Following on from Phase 4, the identification of where energy storage could be located can be carried out. Phase 5 will involve a screening study to identify where energy storage is likely to be beneficial.

The most detailed analysis is carried out in Phase 6, where the detailed attributes of the energy storage connections are determined and tested to determine the ultimate benefits to the power system.

Note that even though the analysis is carried out on an all-island basis, only dispatch down data for Ireland is documented in this report.

2.1 Constraint Analysis Tool (CAT2)

Central to this study is the grid simulation engine required for modelling – where the power system is modelled in a constrained mode of operation.

Our in-house Constraint Analysis Tool (CAT2[6]) is used to assess dispatch down on the power systems in Ireland and Northern Ireland. We continually review, update and benchmark CAT2 as required to match procedures in the system operator's (i.e., EirGrid and SONI) control rooms.

CAT2 carries out a fully constrained simulation of the all-island power system – calculating detailed dispatch-down information on surplus, curtailment and constraint. The key strength of CAT2 is in determining constraint – i.e., due to transmission network limitations.

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[5] The grid model simulation is run in two different modes – constrained and unconstrained. The unconstrained analysis is used to determine the magnitude of circuit loading or substation voltage. Whereas constrained analysis determines what generation (or other grid model attributes, such as load) changes are required to optimally keep the power system within limits.

[6] CAT2 is developed in-house by TNEI using the Siemens Power System Simulator for Engineering (PSS®E) and Python scripting.

Rather than relying on a general optimisation procedure, an enhanced feature of CAT2 is in mimicking how the EirGrid and SONI Wind Dispatch Tool (WDT) manages dispatch down, particularly constraint:

- Renewable connections are grouped together depending on their effectiveness to alleviate potential thermal overloading on the transmission network.
- The effectiveness is a measure of the change in the renewable generation output relative to the change in the level of the network (e.g., a particular circuit) loading. This effectiveness is also commonly known as a shift factor.
- The system operator uses the constraint groups in the WDT to allow for the quick, practical and appropriate application of generation constraint in real time system operations.
- Constraint groups are implemented and applied in the study model, as per this system operator approach.

For clarity, the following terms are used throughout the study:

- **Constraint** denotes wind and solar power reduction due to transmission network thermal overloading (congestion).
- **Curtailment** denotes wind and solar power reduction due to system-wide operational limits such as the SNSP threshold.
- **Surplus** (also known as oversupply) denotes wind and solar power reduction due to generation demand balance requirements.

Under the EU's Clean Energy Package, it has been mandated that priority dispatch of renewable generation will continue to apply only to generators that connect prior to 4th July 2019 (Article 12). This creates a new type of generator for consideration in the dispatch process – the non-priority dispatch renewable generator, connected after 4th July 2019.

- During generation reduction for surplus reasons, a distinction is made between the treatment of priority and non-priority renewable generators, and non-priority generators are reduced ahead of priority generators. Within these two categories of generation, surplus is applied pro-rata across the all-island system for all generators in the category.
- During curtailment or constraint of renewable generation, no distinction is made between priority and non-priority generators, and dispatch down is applied pro-rata across either the all-island system (in the case of curtailment), or across the relevant transmission nodes (in the case of constraint).

Based on the methodology underpinning the recent EirGrid ECP 2.3 constraint reports, generation reduction for surplus and curtailment is applied prior to constraint identification.

Therefore, CAT2 works by calculating renewable generation reduction due to surplus and curtailment in the first instance and then due to constraint. Even though surplus and curtailment are key aspects in the dispatch down of renewable generation, the focus of the study is on the calculation of power reduction due to constraint. The process of grandfathering of constraint has been excluded from the analysis. The exact methodology and logic on how the grandfathering approach will be implemented is still ambiguous.

2.2 Scenario design

A single future scenario describing a high renewable generation power system forms the basis of our energy storage analysis. Ireland's Climate Action Plan (CAP) defines the renewable generation levels - therefore, onshore wind was assumed to be 9 GW, solar was assumed to be 8 GW and offshore wind 5 GW.

Similarly, EirGrid and SONI's SOEF v1.1 defines the transmission network build-out – therefore the majority of projects described in SOEF v1.1 are assumed to be place in our grid model.

Early in the study, variations in interconnection export operation were tested to gauge levels of surplus, curtailment and constraint - and to arrive at the appropriate balance for an energy storage study. Predictably, surplus emerged as a dominant characteristic of our scenario design. Figure 3 illustrates how high levels of surplus can lower constraint. Due to the absence of operational constraint in our model, curtailment is negligible.

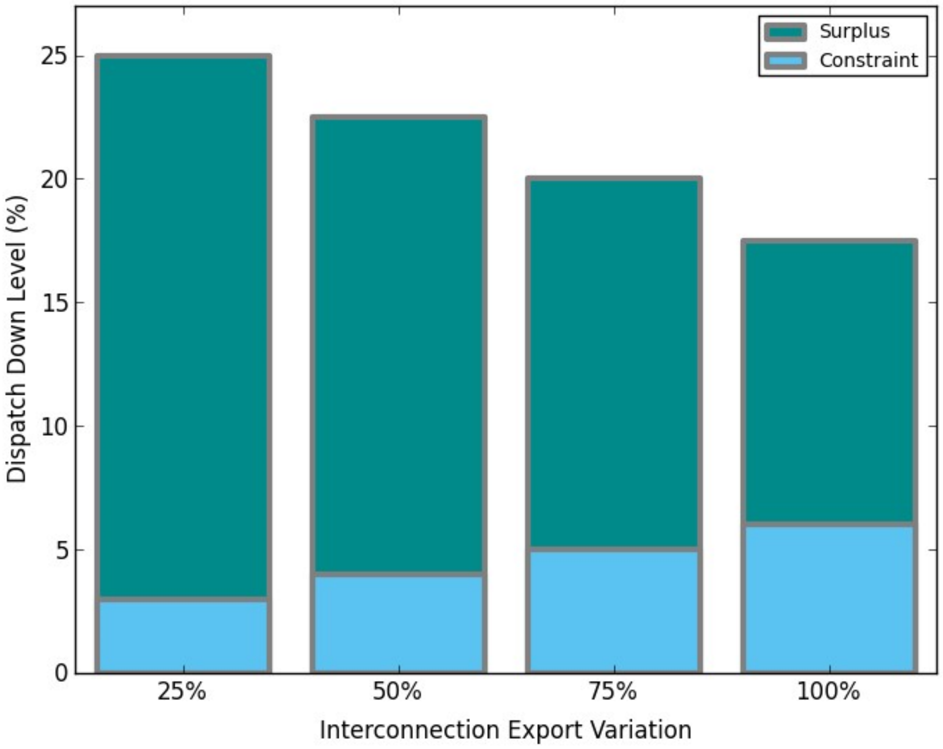

Figure 3 - Surplus and constraint relationship due to interconnection export variation

Producing a scenario with an abundance of surplus, and therefore minimal constraint, is counterproductive to our analysis in Approach A– where the purpose is to examine how energy storage can mitigate constraint. In particular, due to the uncertainty that surrounds the credibility of high levels of surplus and the high likelihood of high constraint levels – for example, due to maintenance outages and the possibility of delays in some renewable connections and infrastructure delivery.

Therefore, to develop a model with high renewable generation and a credible level of constraint, an approach that includes high demand flexibility and optimal interconnection operation at periods of high renewable generation is assumed to minimise surplus and produce a credible level of constraint.

2.3 Operational schedule

The key input for CAT2 is an operational schedule that represents the hourly MW variability of the three non-network categories of the scenario design – i.e., electricity demand, generation and interconnection.

An hourly schedule emulates the main characteristics of a market schedule, based on the following key considerations:

- An hourly demand profile forecast,
- Hourly solar and wind (onshore and offshore) profile data based on typical capacity factor data for Ireland,
- Conventional thermal generation dispatch[7] based on merit order, and
- Interconnector flows linked to renewable generation availability[8].

In developing the hourly schedule for 2025, ramping constraints are relaxed, allowing large temporal changes in renewable generation – and hence equivalent changes to conventional gas plant and interconnection to offset any generation-demand imbalances.

Applying ramping constraints to the model would likely further increase dispatch down due to curtailment and surplus, thus decreasing constraint levels. This provides further justification for the selection of a scenario with high demand flexibility and optimal interconnection which help to reduce the surplus and curtailment values.

The provision of system services is assumed to be accounted for by low carbon technologies, such as synchronous condensers. As a result there is no requirement in the model for conventional generators to be scheduled to provide system services for voltage regulation, frequency management or system strength mitigation.

2.4 Grid model building

Using the EirGrid and SONI published data, TNEI have modelled a nodal-level representation of the all-island transmission network.

TNEI's network model is based in Power System Simulator for Engineering (PSS®E), a software platform designed to simulate electrical transmission networks.

The model includes the complete all island 400 kV, 275 kV, 220 kV and 110 kV transmission network and interconnectors. The network has the same network connectivity, impedances and ratings as the network information published in *All-Island Ten-Year Transmission Forecast Statement 2021*.

To represent the 2035 study year, we added all projects outlined in the latest SOEF v1.1 roadmap publications – excluding one particular project, a new circuit between Clogher and Srananagh. Circuit technologies such as Dynamic Line Rating (DLR) or power control technologies were assumed to be inactive in the transmission network model. These technologies will help reduce constraint in some areas of the transmission network[9] but the method of operation of these devices is still ambiguous.

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[7] Including unit commitment, economic dispatch and reserve calculations.

[8] In general interconnection is scheduled to ensure generation adequacy when renewable generation is low and to minimise over-supply and curtailment when renewable generation is high.

[9] https://windenergyireland.com/images/files/bridging-the-gap-a4-report-final.pdf

2.5 Grid model simulation

This grid model simulation phase blends the hourly generation schedule with the grid model – simulating how the schedule interacts with the transmission network in Ireland.

A needs assessment identifies the thermal overloading violations on the transmission network. This analysis is based on an unsecured simulation (i.e., thermal loading limits are not enforced but are reported on) using the standard N and N-1 contingency performance tests.

An additional fully secured simulation (i.e., thermal loading limits are enforced) is carried out to complement the needs assessment by calculating generation constraint – again using the standard N and N-1 contingency performance tests. This is effectively a re-run of the needs assessment in an operational mode – identifying specific generators for dispatch-down to keep the system within limits.

During all phases of the analysis, N and N-1 analysis will be the primary grid performance tests. Other performance tests outlined in the EirGrid Transmission System Security and Planning Standards[10] (TSSPS), e.g. the impact of maintenance outages, is not be considered.

2.6 Energy storage location identification

This phase identifies locations that are likely to be beneficial for the connection of energy storage technologies.

Using the results of Phase 4, hypothetical energy storage models were placed at up to 20 locations.

These locations were chosen, using existing transmission stations in the vicinity of high circuit loading and generation constraint, to minimise the most onerous instances of generation constraint.

A further fully secured simulation, using the standard N and N-1 contingency performance tests, was carried out to assess the relative performance of the hypothetical energy storage candidates.

For each hour of the simulation the analysis charges and discharges the hypothetical energy storage units optimally with the objective of (where possible) minimising loading throughout the grid.

2.7 Energy storage benefit calculation

Two different modelling approaches (A and B) are considered when simulating our energy storage portfolios. Approach A focuses on constraint mitigation only and Approach B considers the mitigation of all dispatch down categories – i.e., surplus, curtailment and constraint.

2.7.1 Approach A

Charging or discharging is only activated when thermal overloading occurs on overhead lines, underground cables or transformers – i.e., the objective is to manage the loading on these categories of circuits when thermal ratings are exceeded.

This is a conservative approach – because storage units can always enter charging mode when there is high loading while not exceeding thermal ratings. Hence the benefits identified by this approach should be treated as minimum benefits. In real time operation, the energy storage candidates are likely to experience more frequent operation like those identified in Approach B.

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[10] https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-Transmission-System-Security-and-Planning-Standards-TSSPS-Final-May-2016-APPROVED.pdf

2.7.2 Approach B

In this approach we exhaust the capabilities of our energy storage portfolio. Charging or discharging is activated to minimise surplus, curtailment and constraint, based on the following logic:

- The main priority of our energy storage portfolio is to enter a charging mode of operation to minimise surplus and curtailment as much as possible – in some cases, depending on the location, the transmission network can limit this ability.
- Once energy storage charging has dealt with surplus and curtailment, if there is some remaining charging capability, our model will use energy storage to reduce thermal overloading (on overhead lines, underground cables or transformers).
- To enter a discharging mode of operation, the would-be conventional generation dispatch can be displaced. In many hours there is not always a sufficient volume to allow a full discharge – hence this can take a number of hours to achieve.

3 Modelling Assumptions

This section outlines the assumptions that underpin the key modelling components of our scenario design. In many instances, our approach to assumptions aligned with the data published in EirGrid and SONI's *Shaping Our Electricity Future*[11] (SOEF) version 1.1. In some instances, due to the purpose of our study, we sometimes adopt alternative, but equally credible, assumptions.

3.1 Interconnection

There are two types of interconnections considered in our grid model, HVAC connecting Ireland and Northern Ireland and HVDC connecting the all-island power system to Britain and France.

3.1.1 HVDC interconnection to Great Britain and France

Four HVDC interconnectors were assumed in our model. The two existing interconnectors (EWIC and Moyle) and the two planned interconnectors (Celtic and Greenlink) were assumed in our scenario. Further interconnection, as was assumed in SOEF v1.1, was omitted from our model.

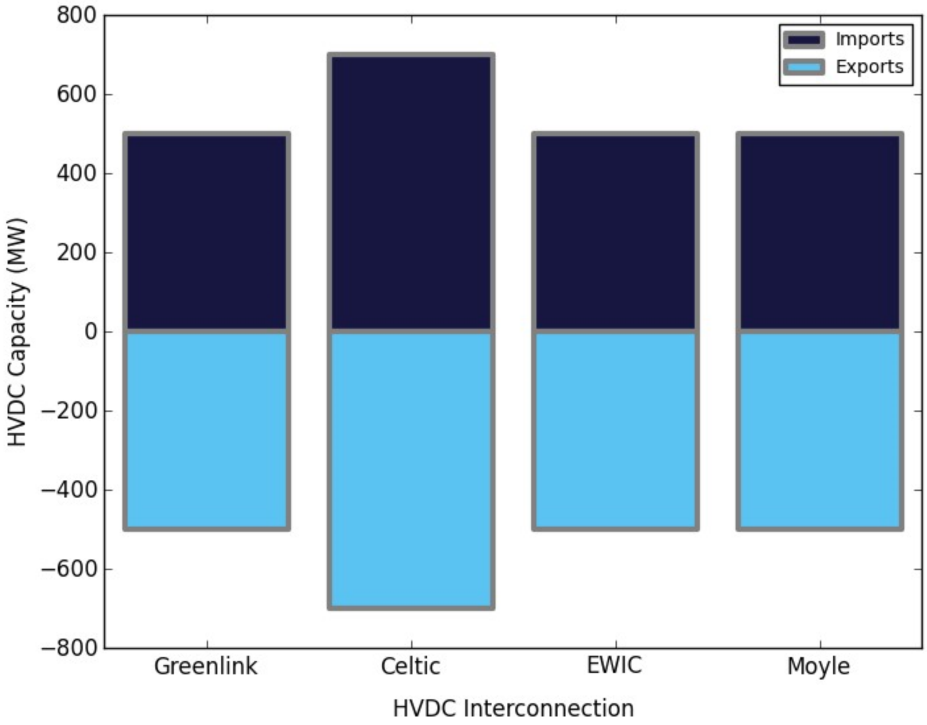

Figure 4 – All-Island HVDC interconnection assumptions

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[11] https://www.eirgridgroup.com/site-files/library/EirGrid/Shaping-Our-Electricity-Future-Roadmap_Version-1.1_07.23.pdf

It is difficult to predict, with adequate confidence, the power flows on HVDC interconnectors to other power markets. A key consideration for interconnector operation in our CAT2 simulation is surplus – and the potentially high levels of surplus when renewable generation significantly exceeds the electricity demand.

In early study simulations, we considered various interconnection strategies – varying from optimistic to pessimistic operation. The objective was to arrive at a modelling philosophy underpinning interconnection representation to ensure that interconnector flows do not disproportionately influence the calculations.

- To recognise the limitation of interconnector capability, we assume that imports and exports are limited to 75% capability - similar to EirGrid ECP reports. Imports will mainly be activated when there is a shortage of conventional generation and exports will mainly be activated to avoid surplus and curtailment – i.e. during times of high renewable generation.
- To focus on network constraint, CAT2 was set up to always activate interconnection to minimise surplus, to ensure a reasonable level of constraint throughout the model.

3.1.2 HVAC interconnection between Ireland and Northern Ireland

We assume that the Letterkenny – Strabane and Corraclassy – Enniskillen 110 kV interconnectors are set via their control systems to 0 MW flow and therefore have zero power flow at all times. This is in line with the standard approach in the EirGrid and SONI control rooms where these interconnectors are infrequently used to exchange power and when they are used the power flow is minimal (typically below 15 MW). The planned second North South Interconnector is included in the analysis. The power flow between Ireland and Northern Ireland is determined by the generation schedule and is kept within thermal rating limits.

3.2 Fossil fuel generation

In a net zero future, all the existing operational constraints (for example, generating units that have a must-run status) are assumed to be removed. At present the following operational constraints for fossil fuel conventional generators exist on the system:

- **System Non-Synchronous Penetration (SNSP):** Currently at 75%, we assume that the SNSP limit can be removed. This metric is an approximation for renewable generation levels and system strength. The emerging system services that will address this and other operational constraints planned by EirGrid and SONI are assumed to remove the need for an SNSP limitation.
- **Rate of Chage of Frequency (RoCoF):** Currently at 1 Hz/s, we assume that the RoCoF limitation remains at 1 Hz/s. There is no explicit requirement for conventional units to be utilised to maintain RoCoF below 1 Hz/s. Our model assumes that batteries and other zero carbon technologies can satisfy this requirement, removing the need for conventional units to be utilised for RoCoF purposes.
- **Inertia:** Currently at 20,000 MWs, we assume that the inertia floor remains at 20,000 MWs. Existing and future synchronous condensers (like ESB’s new synchronous compensator at Moneypoint) can be utilised to satisfy this requirement, removing the need for conventional units to be utilised for inertia purposes.
- **Minimum Number of Units (MUON)**: currently seven[12] (four in Ireland and three in Northern Ireland), it is assumed that the minimum number of units requirement is reduced to zero. It is assumed that the services that conventional units currently provide, such as inertia, system strength, short circuit level, frequency regulation, reserve provision and voltage control can be provided by zero carbon technologies such as synchronous condensers and batteries.

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[12] A seven-set policy is currently under trial in the control centers

To ensure generation adequacy, additional hypothetical generation is assumed at various existing locations for gas plant. These are immaterial to the energy storage analysis – as they are only scheduled infrequently at periods of low renewable generation and peak electricity demand. The merit order used for unit commitment and generation dispatch after the scheduling of renewable generation categories is assumed to be similar to the present day.

3.3 Renewable generation

The foundation of our scenario is renewable generation. Onshore wind, offshore wind and solar generation are the three dominant sources of renewable generation. Figure 5 describes the installed capacities connected to the Ireland and Northern Ireland transmission systems.

Hub-connected wind generation, similar to the SOEF v1.1 approach was not considered. In constructing the hourly schedule, all renewable generation connections in Ireland and Northern Ireland are scheduled based on the published ECP 2.1 hourly capacity factor data for 2015.

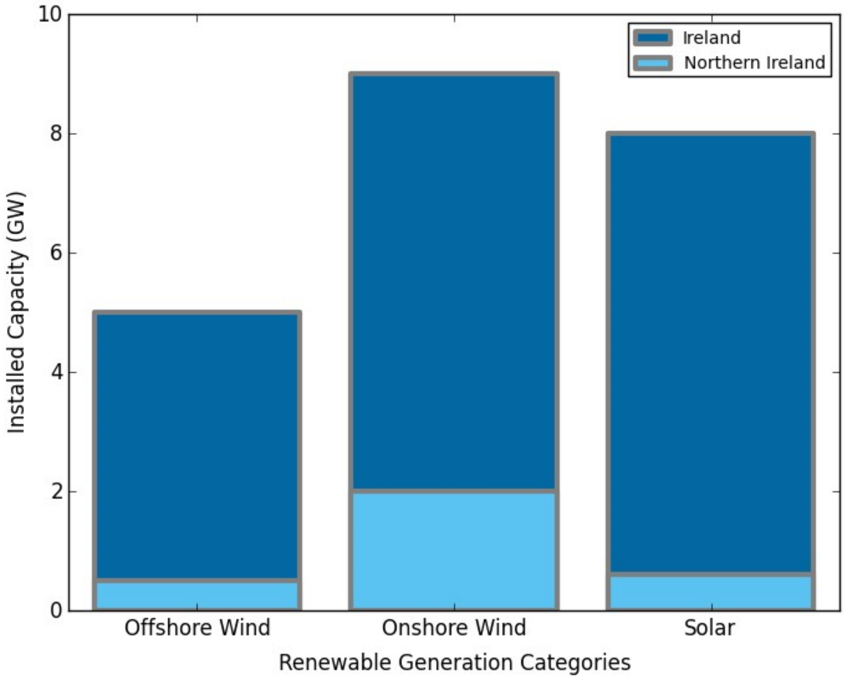

Figure 5 – All-Island renewable generation assumptions

The initial onshore wind generation portfolio is developed based on existing connections and future connection data available up to an including ECP 2.3. To make up CAP 23 targets, Wind Energy Ireland pipeline connection data was used.

The initial solar PV generation portfolio is developed based on existing connections and future connection data available up to an including ECP 2.3. To make up CAP 23 targets, micro-scale solar generation was assumed based on the SOEF v1.1 approach.

Offshore wind generation is modelled based on all the Phase 1[13] project applications – those successful and those unsuccessful in ORESS1. Additional offshore wind generation is assumed to be split between the Knockraha and Great Island 220 kV station – in line with the ORESS2 direction.

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[13] https://www.cru.ie/wp-content/uploads/2021/10/CRU21112a-EirGrid-Offshore-Phase-1-Projects-Grid-Connections-Assessments-March21.pdf

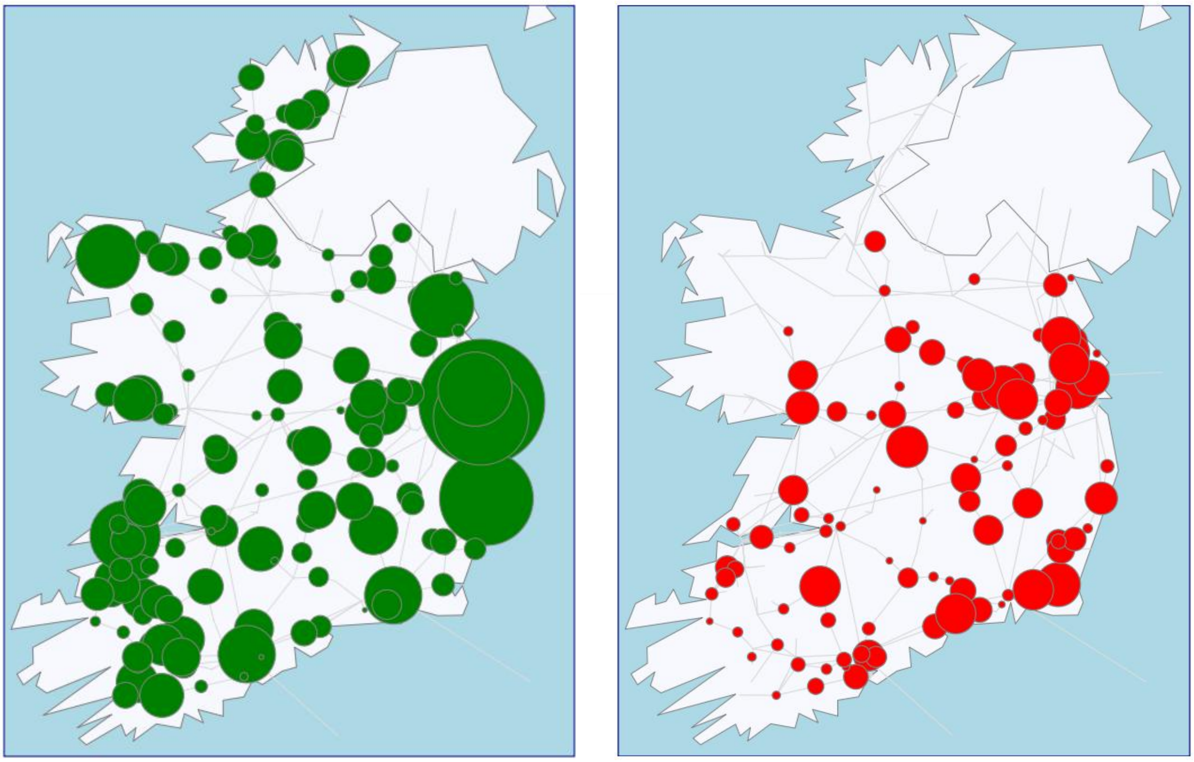

Figure 6 – Distribution of wind and solar (excluding micro-scale) connection locations in our grid model

3.4 Energy storage model

Our energy storage model behaviour is based around the current understanding of lithium ion-based technology. For all studies we assume an energy storage charging and discharging capability of 100 MW at each candidate location.

We assume that the round-trip efficiency (RTE) tends to decrease as the energy storage duration increases. As shown in Figure 7, we consider a range of operating capability, from short-duration to long-duration, including 4-hour, 8-hour, 16-hour, 24-hour and 100-hour variations. This approach ensures that the analysis captures a broad range of the technology capability. The 16-hour, 24-hour and 100-hour options are likely to be a technology beyond current lithium-ion capabilities.

Energy storage connections are not considered in our baseline study for congestion management. However, some existing battery storage is assumed throughout the power system for generation reserve, generation adequacy and voltage regulation purposes – and ensures that curtailment is negligible. Such battery storage is excluded from the congestion management phase of the analysis.

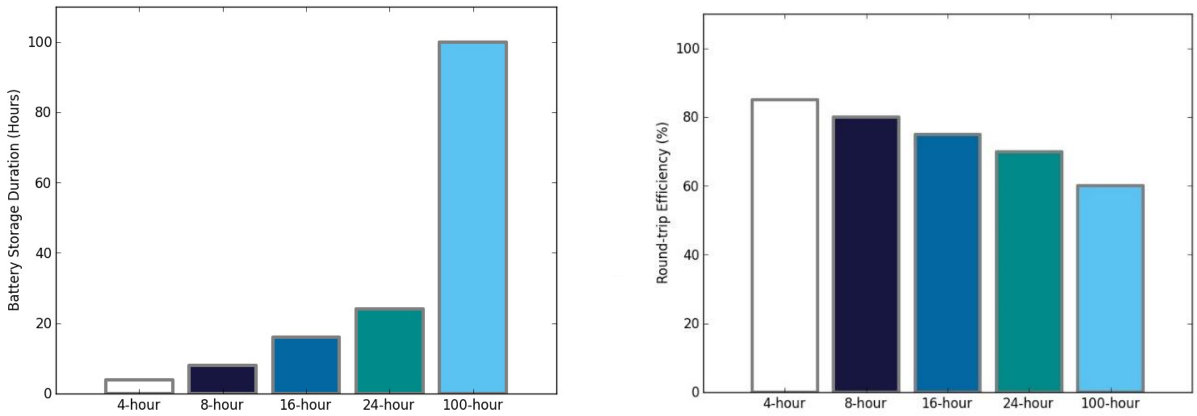

Figure 7 – Energy storage congestion solution options

The Turlough Hill pumped storage is modelled in a traditional manner. All four units are assumed to be available at all times, generating at minimum output during the day (i.e., at least 5 MW per unit), climbing to a maximum output at evening peak periods and all units switching towards maximum pumping mode throughout the night.

3.5 Electricity demand

The nodal distribution of electricity consumption (or demand) is based on the grid models as published by EirGrid and SONI.

The annual All-Island demand in TWh for year 2035 is used[14]. The demand forecast for 2035 is based on the median forecast projections outlined in EirGrid's Generation Capacity Statement (GCS) 2022 – 2031. This is standard practice for transmission planning in EirGrid and SONI.

The demand profiles for both Ireland and Northern Ireland are based on their actual 2015 demand profiles. These are then adjusted to get an annual energy value as per the annual demand in TWh for 2035. Figure 8 shows how the key demand categories for Ireland and Northern Ireland relate to each other.

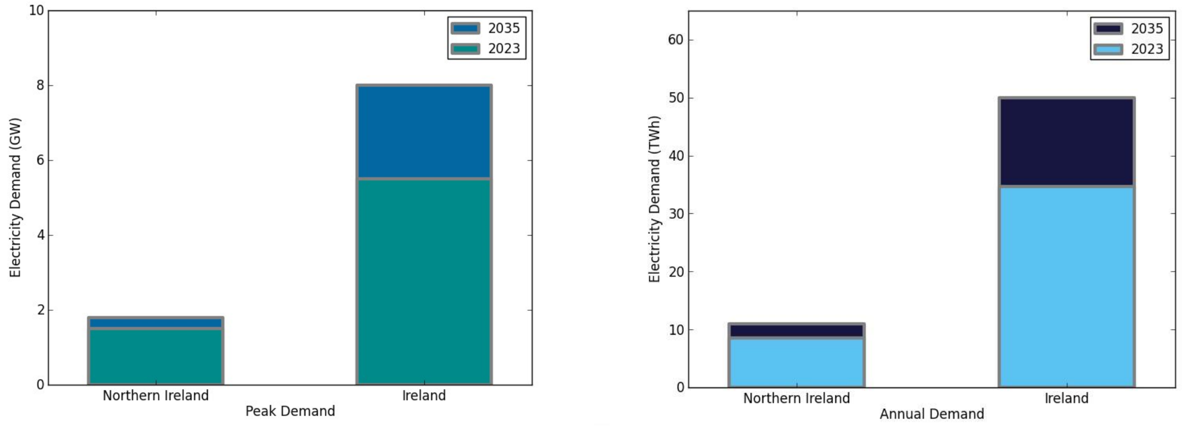

Figure 8 - All-Island electricity demand assumptions

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[14] Based on the latest Generation Capacity Statement information.

Data centre connections are based on the connections present in the published PSS®E network files and are scaled *pro rata* to meet the forecasted build-out level in the median forecast in the GCS.

Traditional industrial loads, such as manufacturing and pharmaceuticals, are assumed to be the same as those described in the published PSS®E model data – assuming no new connections.

Demand growth due to electric transport and heat pump technologies are assumed to be non-disruptive – and incentivised to avoid impacting the peak load behaviour.

3.6 Grid performance tests

For each hourly snapshot, in line with the EirGrid TSSPS[15], our grid analysis examines the thermal loading and voltage performance under intact (N) and single contingency outage (N-1) conditions.

In reality, the maintenance (or planned outage) of transmission network equipment and generators creates a more fragmented network topology – resulting in situations that frequently increase generation constraint.

Hence the constraint data calculated in this analysis should be considered as a minimum level of constraint – and therefore expected to be higher in operational reality. Subsequently, the derived energy storage benefits are also conservative – and are expected to be higher in real time operation.

3.7 Reserve requirements

At present, the rule is that the primary and secondary operating reserve[16] on the all-island power system is 75% of the largest single infeed (LSI). The system operator (e.g., EirGrid) organises this reserve to ensure that the transmission system remains within operating security standards[17] limits in the event of the N-1 loss of the LSI.

In the future power system, where the LSI increases (e.g., due to the Celtic interconnector) additional reserve capability is required. It is also possible that the 75% limit will be increased to 100%. The 75% limit is based on an assumption of overprovision of reserve from conventional generators, which historically have overprovided during system events. However, in a fully renewable system where renewable generators interface with the system through power electronics, it is likely that over provision will no longer occur and the required reserve requirement may increase to 100%. Due to need to minimise operational constraints, much of this reserve will have to be sourced from demand-side management and battery storage arrangements.

The remaining system services, such as SSRP (steady state reactive power) and ramping requirements, are assumed to be sourced from zero carbon sources. In our model, this ensures that no conventional generation units need to be dispatched for system services purposes.

The reserve requirement is modelled at the scheduling phase - where unit commitment and economic dispatch is simulated in our model.

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[15] Transmission System Security and Planning Standards

[16] Primary Operating Reserve (POR) is defined as the MWs that can be provided from 5 – 15 seconds following a system event. Secondary Operating Reserve (SOR) is defined as the MWs that can be provided from 15 – 90 seconds following a system event.

[17] https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid_Operating-Security-Standards_2021.pdf

3.8 Hydro generation

The traditional hydro generators throughout the island are modelled based on standard EirGrid rules of thumb. Typically, most units are on-line during winter periods and half the units are on-line in the summer period. Such is the scale of hydro generation, the scheduling of this generation category tends to have a minor impact on the results of power simulations.

3.9 Hydrogen generation

Hydrogen generation and corresponding electrolysis demand was not assumed in this scenario design. The future locations of this technology and how it will operate on the power system is yet to be fully defined.

4 Results and discussion

In this section we discuss the main results of our analysis. Initially we present the constraint, curtailment and surplus data from our baseline scenario - without the presence of energy storage.

We use the baseline scenario to identify energy storage locations that maximise the impact on constraint reduction. Due to high levels of surplus, a high volume of transmission network reinforcement and not considering the uncertain impact of maintenance outages[18], our simulation exhibits a modest level of constraint.

Next, we test the impact of energy storage at these locations by varying the duration capability of the technologies. We show the results for both approaches:

- The first (Approach A) uses energy storage technologies only for constraint reduction, whereas
- The second (Approach B) uses energy storage technologies to mitigate the reduction of surplus, curtailment and constraint.

4.1 Unconstrained security analysis without energy storage

In this section we briefly discuss the results of the baseline unconstrained analysis for our scenario in the absence of energy storage technologies. This mode of power system analysis helps visualise the grid that would be required to facilitate the assumed renewable generation portfolio.

Sometimes referred to as a system needs assessment, this analysis does not apply generation constraint. Instead, the power simulation allows renewable generation to flow in an unconstrained manner, sometimes overloading circuits, and therefore allowing for an understanding of how the transmission network is impacted in the future scenario.

The results of our analysis underline how increasingly loaded the future transmission network could be – with greater and more frequent overloading (or binding constraints) materialising simultaneously in all regions of the transmission network. From the national control centre perspective, such a scenario, that already includes a large-scale level of network reinforcement, poses a significant increase to operational complexity.

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[18] Maintenance outages for generators and transmission equipment will increase constraint and therefore the benefit of energy storage.

Figure 9 - Geographic representation of the baseline circuit overloading

4.2 Constrained security analysis without energy storage

In this section we discuss the results of the baseline constraint analysis for our scenario in the absence of battery storage technologies. In this mode of power system analysis, generation is dispatched down throughout Ireland to ensure operating security standards are adhered to.

Our calculations for the key dispatch down categories from our future power system model yielded the following:

- **Surplus** is a dominant characteristic of our power system model – working out at approximately 25%. Or averaging approximately 1 GW per hour. Some individual hours experience up to 8-10 GW of surplus. Figure 10 represents:
  - how surplus varies temporally (in blue) on an hourly basis throughout the study year in our baseline scenario, and
  - hourly surplus data (in green) sorted from maximum (left) to minimum (right), showing that some level of surplus is present throughout half the study year.
- The focus of our analysis is to examine how energy storage can mitigate surplus prior to helping reduce constraint.
- **Curtailment** is negligible due to the absence of operational constraints.
- **Constraint** due to network limitations reached approximately 5%. Figure 10 illustrates the relative magnitude and distribution of generation constraint due to transmission network loading. Regions with significant constraint include the north-west, the mid-east (including the Dublin metro area), the south-west and the south-east.

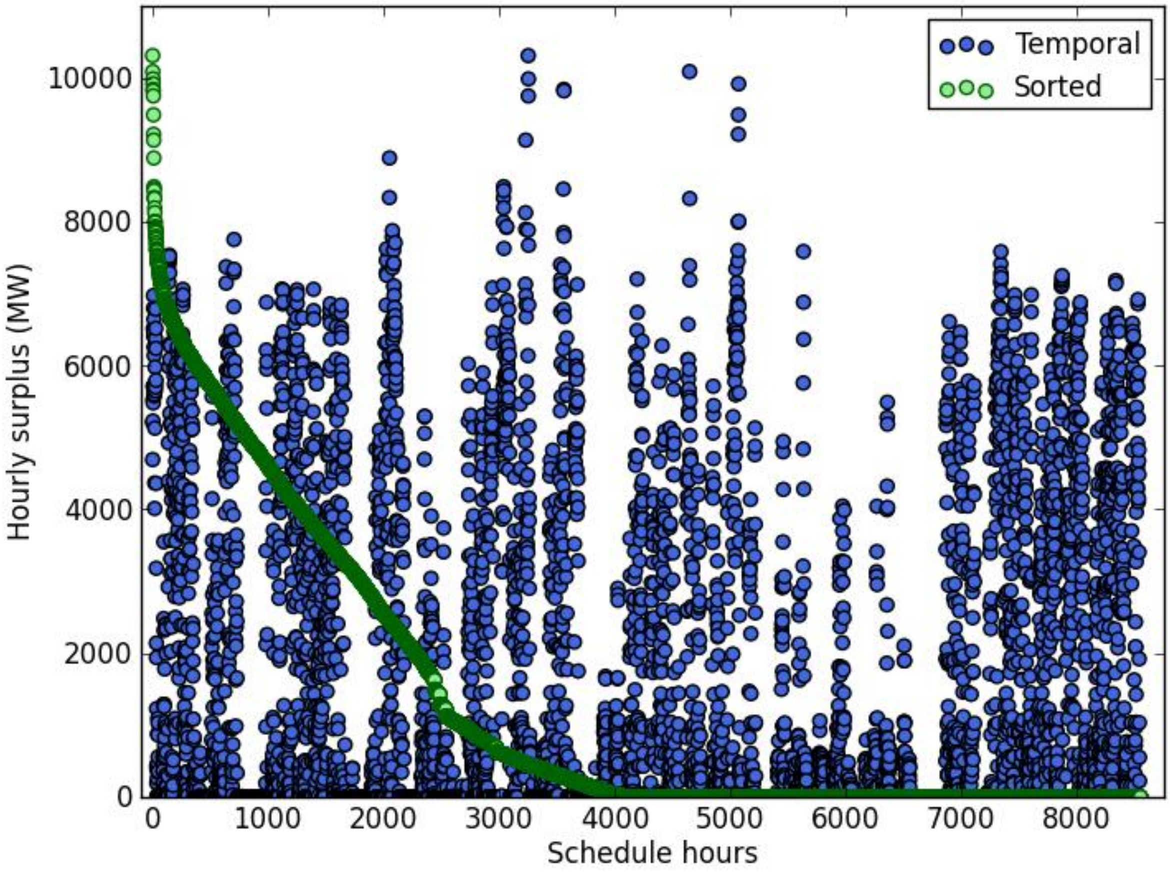

Figure 10 - Hourly surplus levels throughout the baseline scenario

The resultant RES-E[19] figure for our baseline scenario is approximately 80%. A higher RES-E was not achieved due to the high surplus, constraint levels and high demand growth in our scenario. In our analysis of energy storage options, RES-E can potentially increase up to 85%.

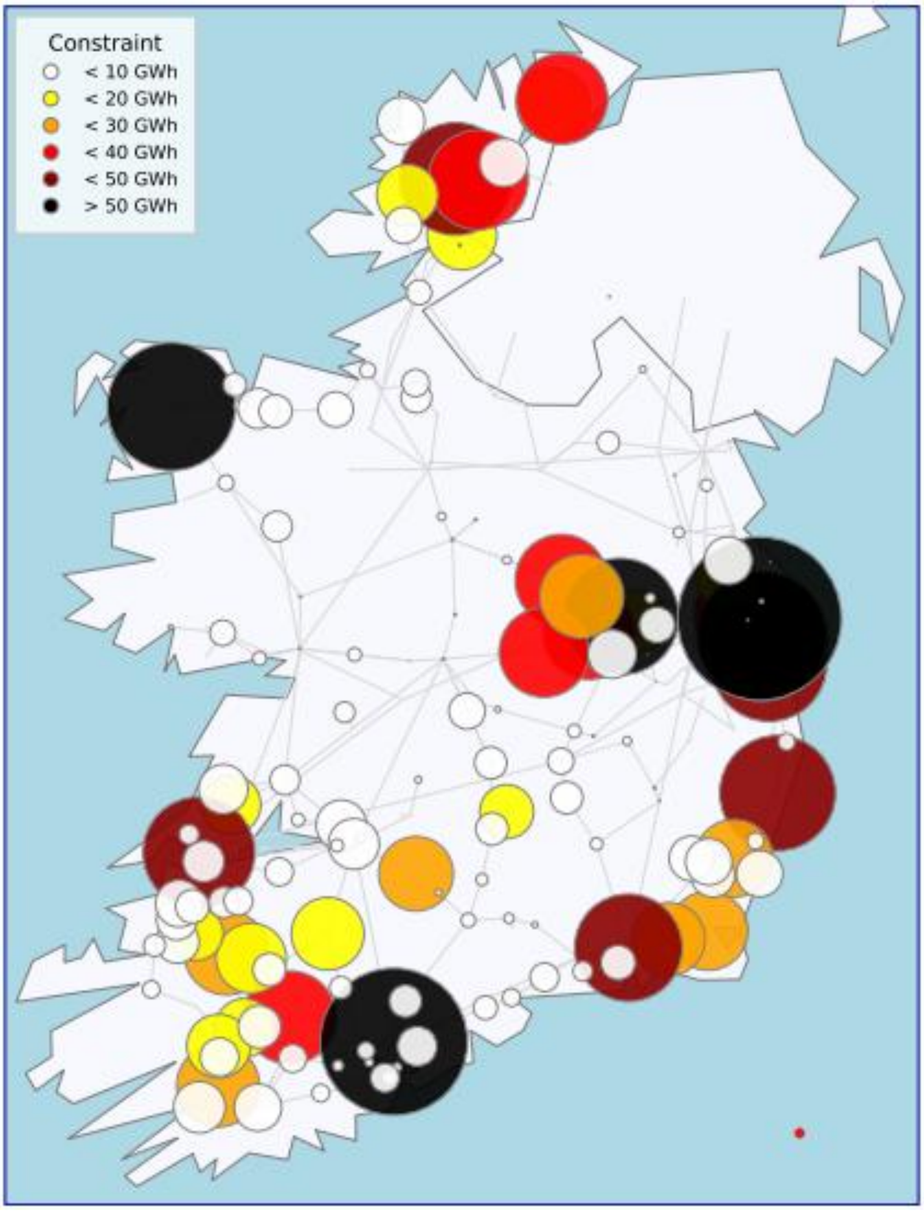

Figure 11 - Geographic representation of the baseline constraint variation

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[19] RES-E is defined as the percentage of renewable generation that is scheduled on the power system following the application of surplus, curtailment and constraint.

4.3 Energy storage location identification

From the baseline dispatch-down analysis, we assessed the nodal constraint data contributing most to the overall level of generation constraint in Ireland. Eighteen locations were selected throughout the transmission network in Ireland as energy storage candidates. The locations we identified experienced constraint levels of at least 20 GWh – contributing to the most significant levels of constraint.

Four main zones for energy storage were identified – the north-west, the mid-east, the south-east and the south-west. The focus on storage candidate locations was assumed to be outside the Dublin metro region, where approximately half the constraint level was identified. We assumed land constraints in the Dublin region could restrict development of storage units of the scale examined in this study.

Figure 12 describes the distribution of the energy storage connection candidates. The following is also noteworthy:

- The storage performance at some nodes is impacted by the storage performance at other nodes throughout the transmission network – in particular those in closer proximity.
- The storage performance for some relatively adjacent nodes could be combined – potentially producing a more effective development albeit a more suboptimal result.
- There are other nodes that could be significantly beneficial for storage. The analysis of other credible scenarios is likely to demonstrate this.

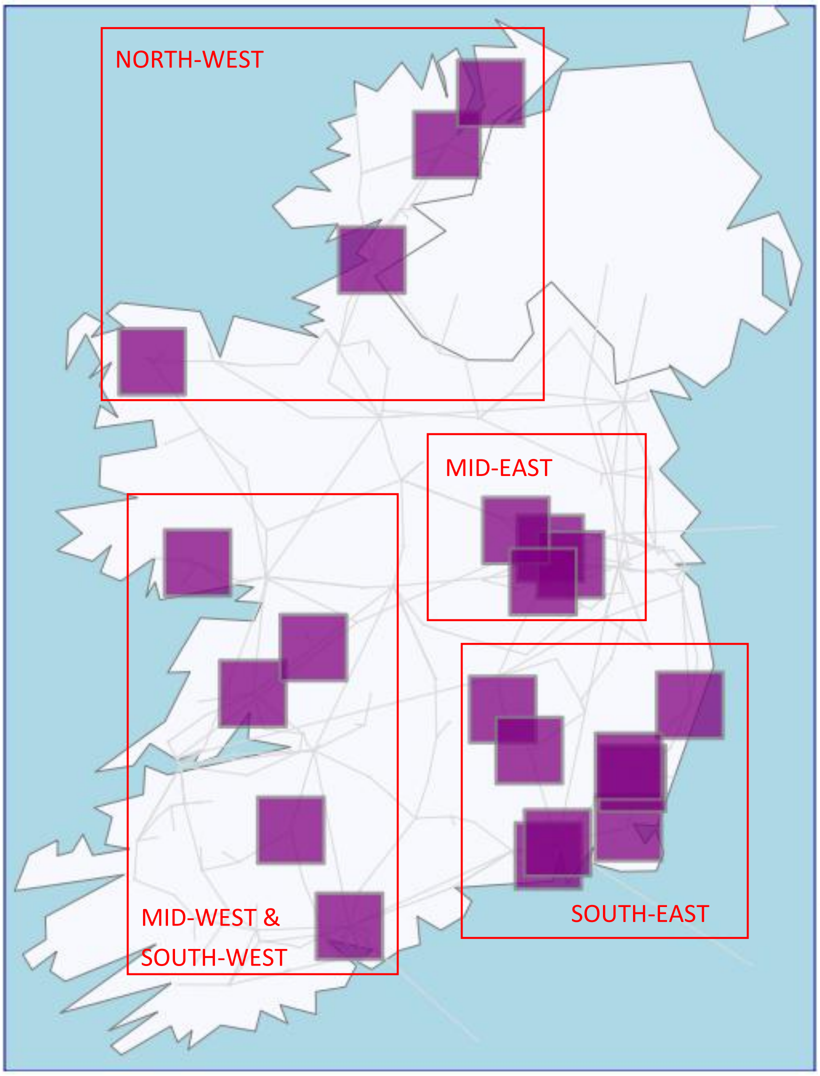


Figure 12 – Geographic representation of the energy storage candidate locations

4.4 Approach A Summary Results

This approach uses energy storage technologies only for constraint reduction. Total constraint due to onshore wind and solar technologies in our baseline scenario is appropriately 2 TWh. Figure 13 below shows the impact of different durations of energy storage on reducing renewable constraints. The longest duration energy storage options reduce this constraint by approximately 50%.

In our analysis of Approach A the utility of lower duration energy storage options tends to max out sooner than the higher-duration equivalent. For example, on average, the 4-hour options are unavailable for more than 15% of the time when needed and 100-hour options are unavailable less than 5% of the time. Hence our assessment of longer duration options is a conservative assessment of their ultimate capability – and shows that they have the capacity to deliver other services, for example to mitigate the high levels of surplus. A regional breakdown of the constraint reductions is provided in the next section.

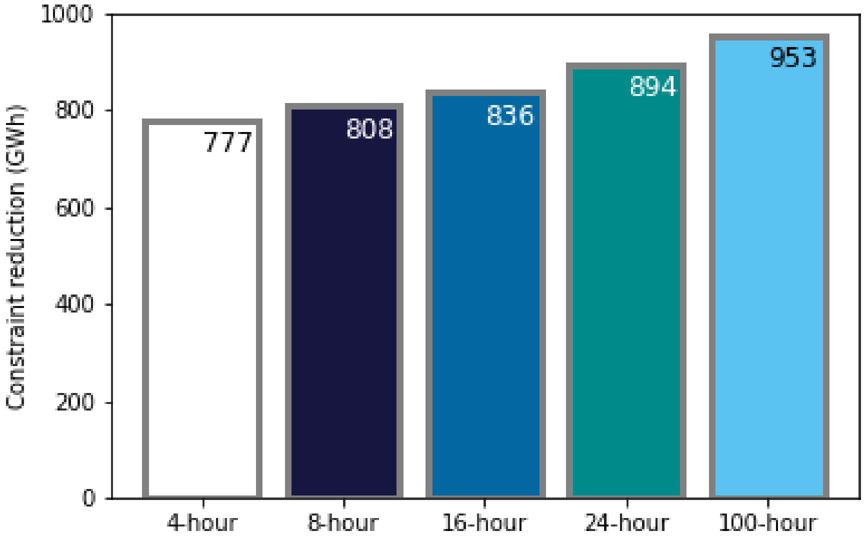


Figure 13 - Summary of battery storage impact on constraint for onshore and solar generation connections

4.5 Approach B Summary Results

In this approach we examined how the various energy storage portfolios could reduce the volume of surplus, curtailment, constraint and conventional generation in our scenario – noting that due to the absence of operational constraints, curtailment is a negligible volume of energy in our analysis. Figure 14 describes how each energy storage technology option helps to lower the volume of surplus and curtailment – showing that the 100-hour option (i.e., with 18 energy storage units) makes significant inroads on the approximate 11 TWh of surplus and resulting in a greater than 3 TWh reduction in surplus.

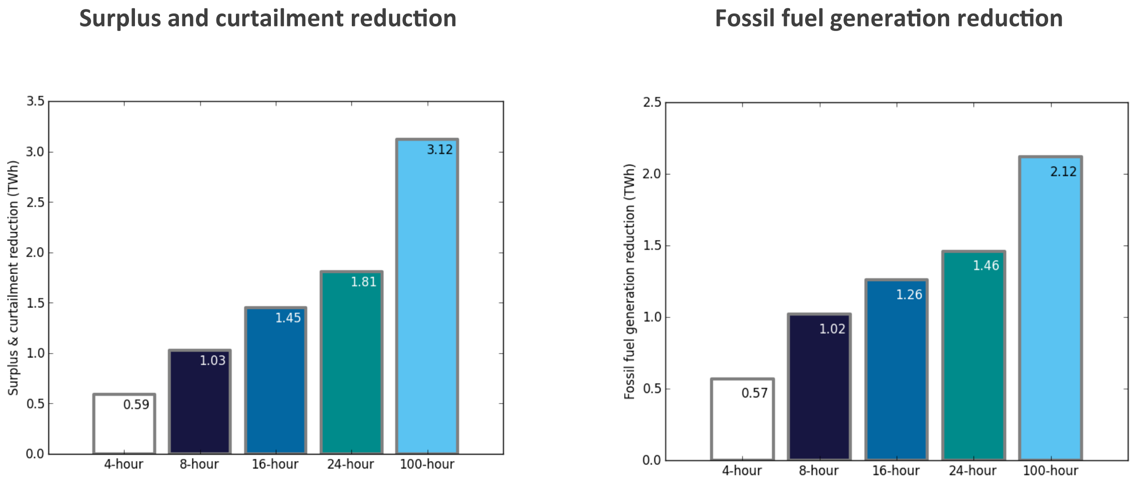


Figure 14 – Impact of energy storage on surplus/curtailment and fossil fuel generation

When the mitigation of surplus and curtailment is prioritised in our model, the following is observed:

- In many hours the low-duration energy storage options become largely redundant for constraint reduction purposes – such is the overwhelming opportunity to charge when surplus occurs. For example, in many hours (with relatively high surplus) the complete energy storage portfolio will fully charge, requiring a later period to discharge.
- When energy storage helps to reduce surplus, constraint throughout the transmission network can increase – sometimes at the locations where the energy storage connections have been assumed, but more so where large-scale offshore is located. So, even though batteries have been identified to minimise constraint, they end up releasing more renewable generation to generate (which is a positive result) but therefore increase loading on the grid. Hence, adequate grid capacity must be requirement to maximise the impact of a large level of long-duration battery storage.
- The 100-hour option demonstrates that technologies at or beyond such ranges are needed when surplus increases beyond the 1 GW/hour towards the 2050 time horizon.
- Our analysis also points to an upper bound limit in deploying a high volume of energy storage for surplus, curtailment and constraint reduction – due to the finite opportunity to discharge. For example, when fully charged our 100-hour energy storage portfolio will need to discharge up to 108 GWh. Due to our high renewable power system, such opportunities (i.e., to displace conventional fossil fuel generation) are not always readily available – for example, in our simulation without energy storage charging or discharging, total conventional gas-fired generation is scheduled (i.e., > 0 MW) approximately 35% of the time.

We also examined the impact of our energy storage portfolio on the output of fossil fuel generation. In our grid model, fossil fuel generation makes up nearly 7.4 TWh of the annual energy schedule. Figure 14 shows how the various energy storage portfolios reduce the need for the mainly gas-generation fleet – with the 100-hour energy storage option reducing Ireland’s fossil fuel dependence by nearly 30% (i.e., over 2 TWh) even when assuming a 60% roundtrip efficiency.

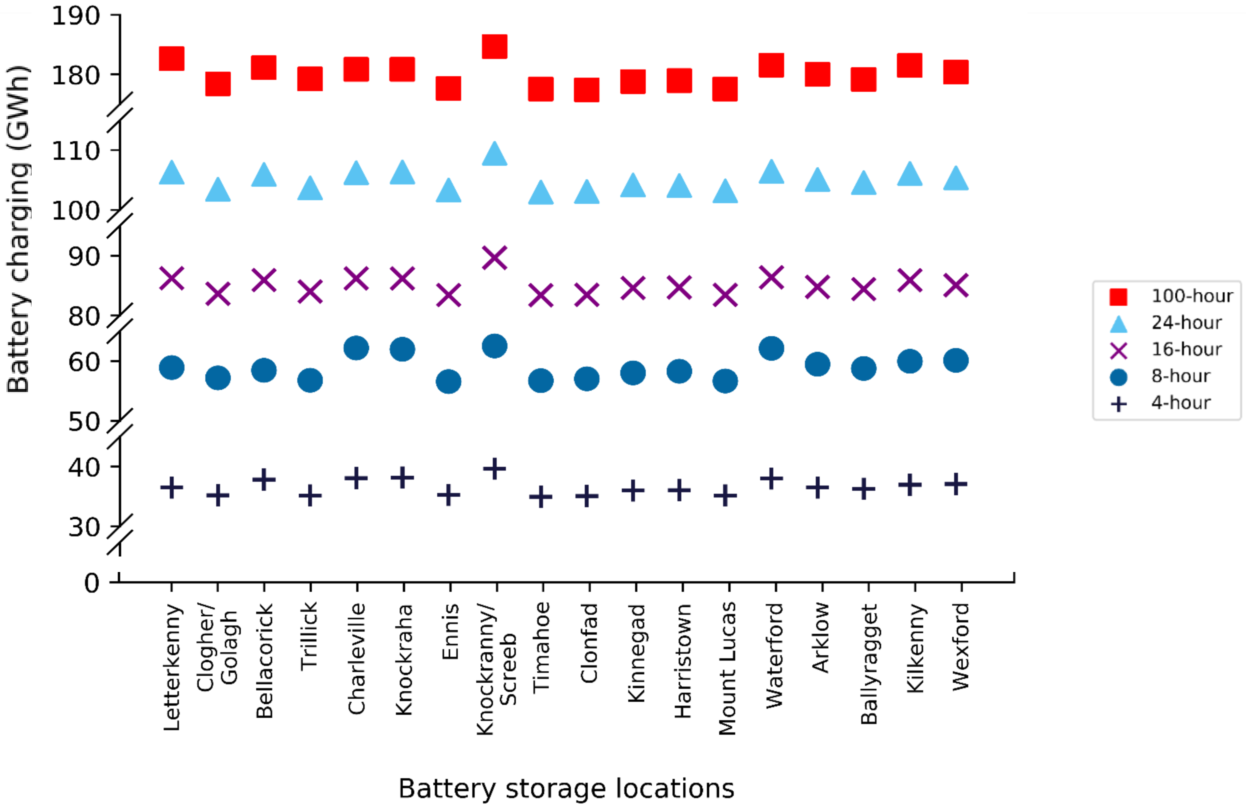


Figure 15 - Summary of energy storage charging activity in reduction of surplus, curtailment and constraint

5 Regional Analysis

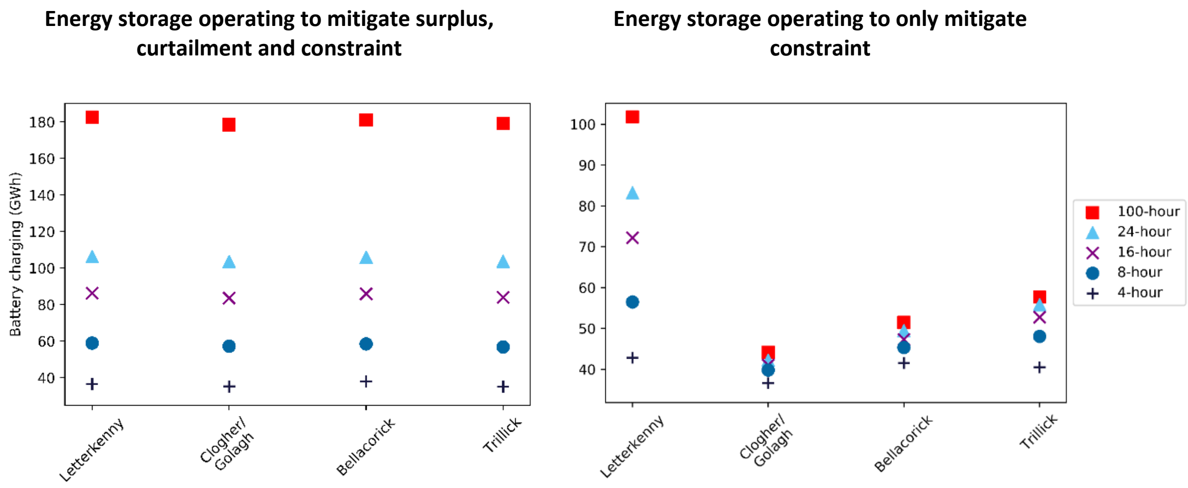
5.1.1 Energy storage in the north-west region

The transmission network in the north-west region primarily consists of 110 kV transmission lines. At present, many of these circuits, particularly those connected to the Cathaleen's Fall 110 kV staton, can be the main cause of congestion for renewable generation. The region is characterised by relatively low demand and high output of onshore wind, which is typically exported from the region towards larger demand centres elsewhere in Ireland. In our model there is negligible solar generation connected in this region.

The 220 kV network in the region, although limited, strengthens the local network and provides security of supply. A significant portion of the SOEF project portfolio is located throughout this region - a combination of overhead line uprates, overhead line upvoltaging[20] and new-build projects. One of the new-builds is the North Connacht project, an underground cable connecting the Moy and Tonroe 110 kV stations. The Clogher – Srananagh 220 kV circuit is excluded from the model due to the high level of uncertainty of delivering such a project. If delivered, these projects can address much of the generation constraint in the region, but not all. Energy storage was modelled at four main 110 kV locations in the north-west region:

- In the Mayo area, at the Bellacorick station, and
- In the Donegal area, at the Letterkenny, Clogher/Golagh and Trillick stations.

Figure 16 shows a comparison of how the various storage options performed in the north-west region. Longer duration storage candidates, such as the Letterkenny 110 kV option, tended to perform best. Similar to all other regions, with such high surplus throughout the island, energy storage units benefit from being large in MW-size and duration.


Energy storage operating to mitigate surplus, curtailment and constraint

Energy storage operating to only mitigate constraint

Figure 16 – Energy storage charging performance in the north-west region

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[20] In Ireland 'upvoltaging' is a term that can be used to describe a transmission network capacity solution that involves increasing the operating voltage of a circuit from 110 kV to 220 kV or 220 kV to 400 kV. This will involve a changes to the conductor, pole/tower structures and substations at each end of the overhead line.

Note that the Bellacorick Special Protection Scheme (SPS) was not assumed to be in operation in our baseline scenario. This approach was assumed to reflect the full potential of future energy storage.

Figure 17 shows how the storage portfolio in the north-west region benefits the level of constraint – experienced by mainly onshore wind generation.

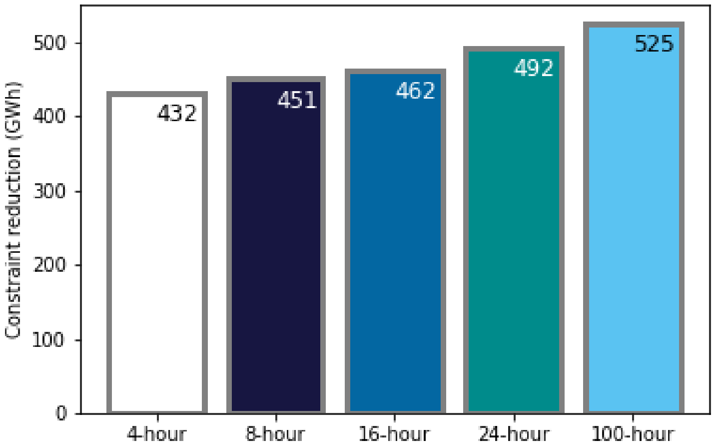

Figure 17 – Energy storage impact on constraint for renewable generation in the North-West region

5.1.2 Energy storage in the Mid-West and South-West regions

The transmission network in the mid-west region mainly consists of 110 kV, 220 kV, and 400 kV transmission infrastructure. At present, the region is characterised as being a key transmission corridor between the west and east of the transmission system. In the coming years, a large volume of renewable generation is expected connect to the local 110 kV network – where many of the circuits are rated below the typical standard rating. In our analysis, many of these circuits experience significant thermal overloading.

The transmission network in the south-west region primarily consists of 110 kV and 220 kV overhead line infrastructure. The region is characterised by significant onshore wind capacity that has connected steadily throughout the last two decades, and relatively recent new-build gas-fired units in Cork. In our scenario, new solar generation connections emerge, and further wind generation (both onshore and offshore) connects in the region. The local network has been significantly reinforced to cater for some of this generation mix, by the building of collector stations, and use of high-temperature-low-sag conductor (HTLS) technology to maximise the capability of the 220 kV overhead lines. The 220 kV network in the region collects onshore wind, offshore wind and solar generation and transfers it either towards the 400 kV[21] network at Moneypoint or towards the Celtic interconnector at the Knockraha 220 kV station in Cork. However, even with this scale of network upgrade, overloading occurs due to the increase in renewable generation.

In our study, storage was modelled at four main locations:

- Two in the south-west region - at the Charleville and Knockraha stations, and
- Two in the mid-west region – on the network west of Galway, and at the Ennis 110 kV station.

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[21] The planned 400 kV circuit between Kilpaddoge (in North Kerry) and Moneypoint is assumed in our transmission model.

In comparison to the present-day transmission network, the level of constraint is greater in these regions due to the increase of future renewable generation, the interaction between the planned Celtic interconnector and local base load fossil fuel generation plant.

Figure 18 shows a comparison of how the various storage options performed in the south-west and mid-west regions with storage in West Galway performing the best. Storage at Knockraha tended to help manage congestion-causing interactions between the Celtic Interconnector and local conventional plant – and not necessarily with the local renewable generation. Generation in the south-west is also sometimes reduced to relieve congestion on the 400 kV grid – at periods where there is too high a power transfer from the south-west towards the Dublin metro area. In some instances, storage was able to mitigate this effect.

Figure 19 shows how the storage portfolio in the north-west region benefits the level of renewable generation constraint – experienced by mainly onshore wind generation.

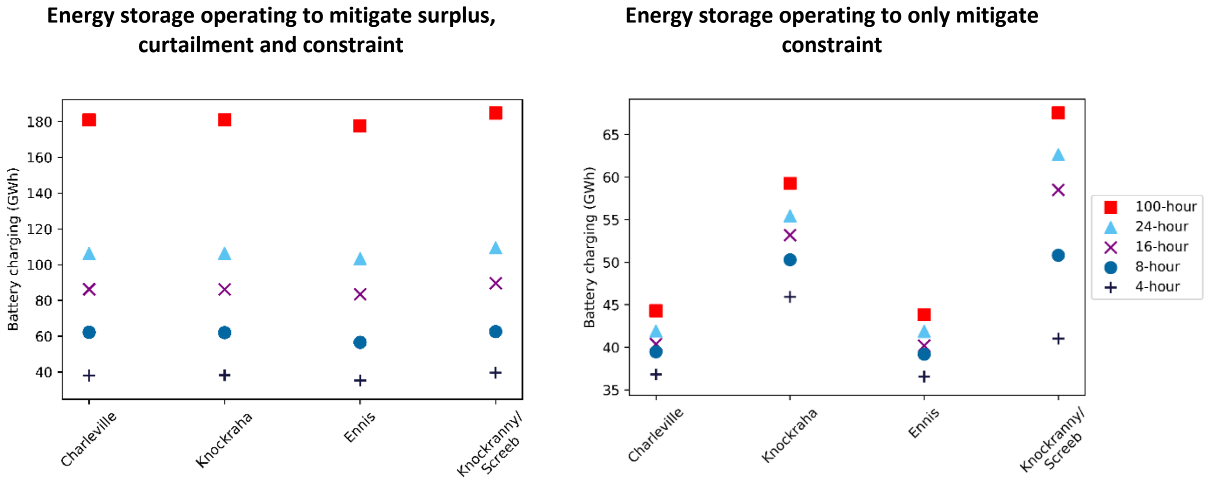


Figure 18 – Energy storage charging performance in the mid-west and south-west regions

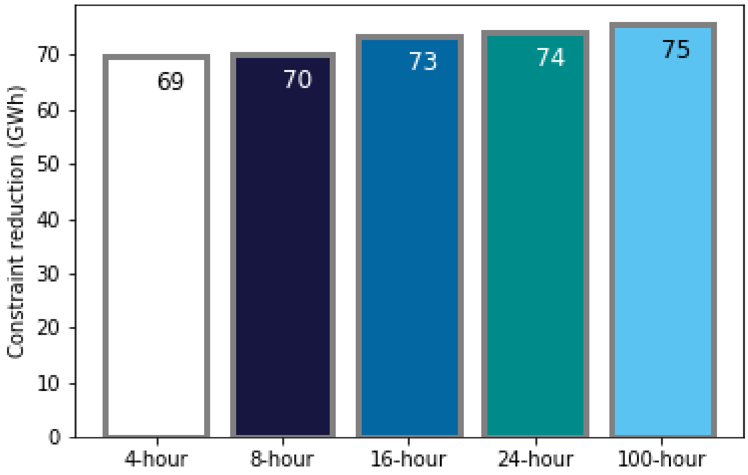


Figure 19 - Energy storage impact on constraint for renewable generation in the mid-west and south-west regions

5.1.3 Energy storage in the south-east region

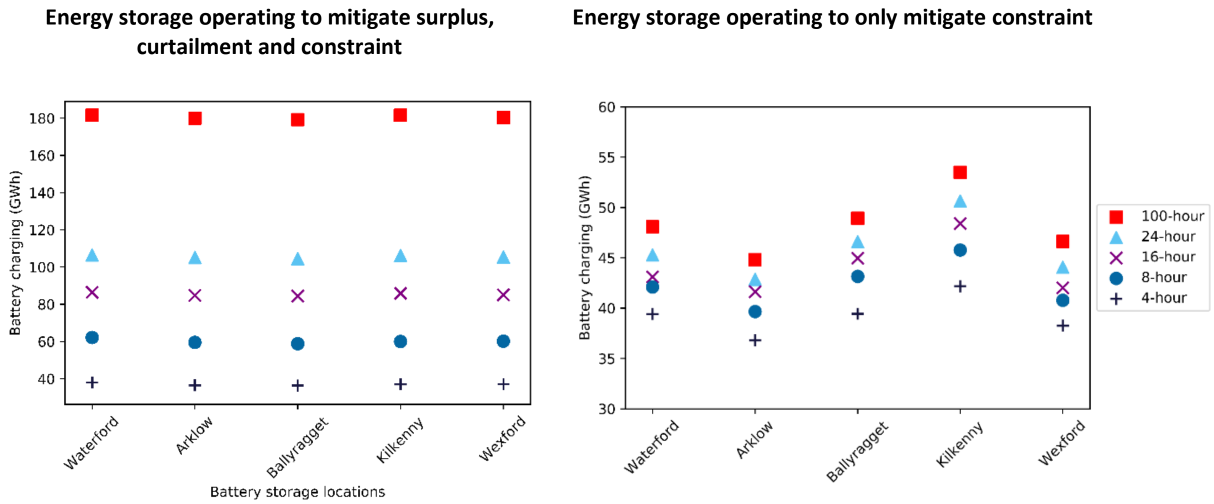
The transmission network in the south-east region consists of both 110 kV and 220 kV infrastructure. The region is characterised as a key transmission corridor between the Cork and Dublin regions, both homes to relatively high demand and fossil gas-fired generation.

In our future scenario, the south-east region becomes a complex hub for renewable generation (including solar, onshore wind and offshore wind), interconnection (i.e., Greenlink) and gas-fired generation. Loading is driven by an interplay between these sources of generation – sometimes working against each other from a network loading point of view.

Storage was modelled at five main 110 kV locations throughout the south-east region.

- In the Kilkenny area – at the Ballyragget and Kilkenny 110 kV stations; and
- Along the south-east coast - at the Waterford, Wexford and Arklow 110 kV stations.

Figure 20 shows a comparison of how the various storage options performed. In our study this region does not experience a significantly high level of constraint due to renewable generation– some of which is caused by the presence of other generation technologies, such as the Great Island power station and the Greenlink Interconnector.



Energy storage operating to mitigate surplus, curtailment and constraint

Energy storage operating to only mitigate constraint

Figure 20 – Energy storage charging performance in the south-east region

Figure 21 shows how the storage portfolio in the south-east region benefits the level of constraint – experienced by mainly onshore wind generation.

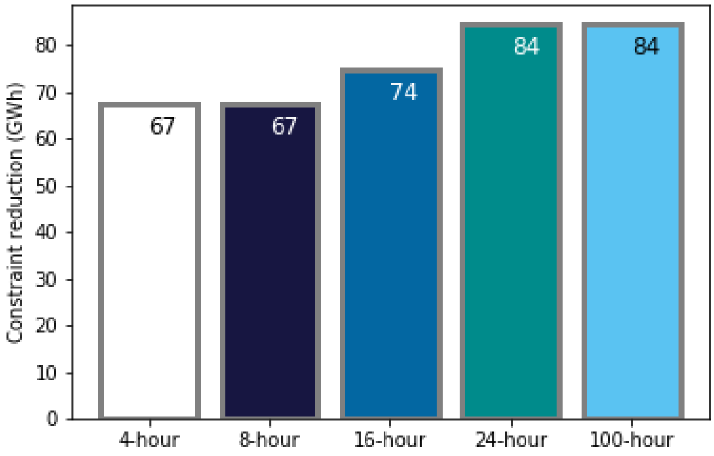


Figure 21 - Storage impact on constraint for renewable generation in the south-east region

5.1.4 Energy storage in the mid-east region

The transmission network in the mid-east region mainly consists of 110 kV, 220 kV, and 400 kV transmission infrastructure. At present, the region is characterised as being a key transmission corridor between the west and east of the transmission system.

In the coming years, a large volume of renewable generation will connect to the local 110 kV network – where many of the circuits are rated significantly below the typical standard rating. In our analysis, many of these circuits, even though assumed to be uprated, experience significant thermal overloading.

Storage was modelled at five main 110 kV locations in the mid-east region – at Timahoe, Clonfad, Kinnegad, Harristown and Mount Lucas.

At present, this part of the transmission network does not experience significant constraint - but in the coming years, with new onshore wind and solar connections, the local 110 kV network will experience significant levels of constraint.

Some network upgrading is planned for the region (such as uprating some of the overhead lines) but will not resolve all the constraint. Due to the level of loading in this region many storage units were chosen to be relatively close to each other electrically – in an effort to mitigate the high level of constraint. Figure 22 shows a comparison of how the various storage options performed.

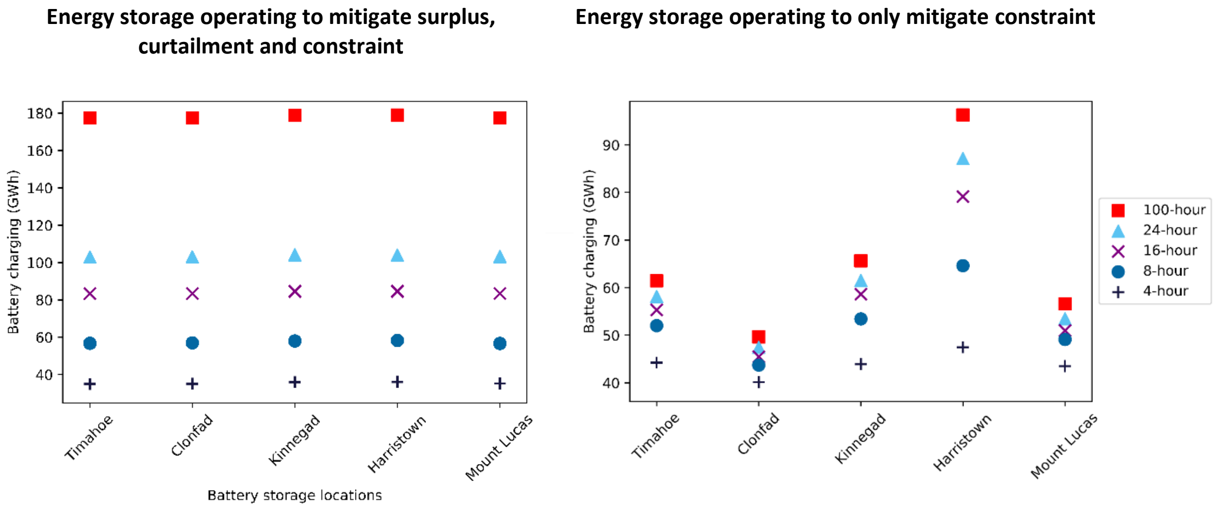


Figure 22 – Energy storage charging performance in the mid-east region

Figure 23 shows how the storage portfolio in the north-west region benefits the level of constraint – experienced by mainly onshore wind generation.

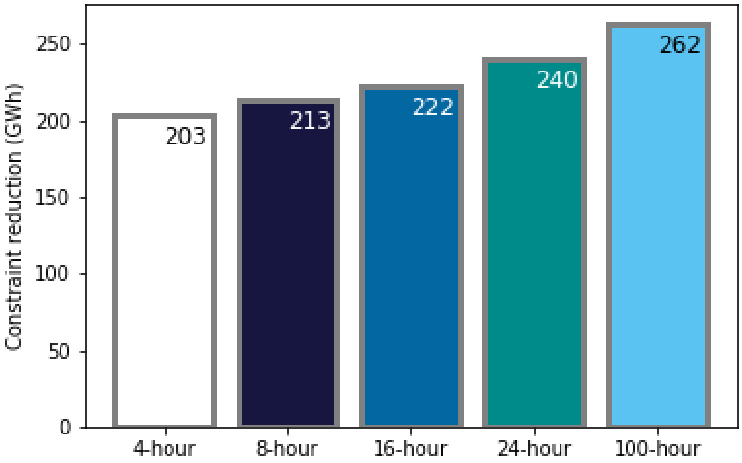


Figure 23 – Energy storage impact on constraint for renewable generation in the mid-east region

6 Other grid services provided by energy storage technologies

In the process of carrying out this grid study, we have qualitatively examined a wide range of additional benefits that energy storage technologies can bring to the power system. This is not intended to be exhaustive, rather it illustrates that dispatch down reduction and congestion management is one of a number of services that energy storage can provide when assessing the full range of benefits these technologies can provide to the grid.

6.1 Active power generation production

Some operational constraints are based on the requirement to have active power generation at particular locations on the grid – to ensure balanced power flows. An obvious storage benefit is the ability to discharge power similar to traditional conventional plant, particularly at evening peak demand periods.

Fast responding energy storage is also a technology suited to deal with large margins of forecast error. This is where the anticipated renewable generation unexpectedly increases or decreases in significant volumes and where conventional plant is not equipped to manage the active power ramping requirements.

Energy storage will play an ever greater role in the reserve provisions of the future power system- in particular in a power system with potentially larger infeeds and outfeeds and no conventional thermal plant in service.

6.2 Voltage and frequency regulation

Current deployment of battery storage is predominantly short-duration in nature, typically 30 minutes in duration, used to provide fast-acting frequency response, voltage regulation and some reserve for fossil fuel-fired generators.

These connections (for example, the battery storage in the midlands) have proven to be highly reliable for grid operation, delivering fast-acting voltage and frequency management when most needed - particularly in the absence of the recently retired peat-fuelled plant.

As the number of conventional thermal units on the power system decreases to accommodate increased levels of renewable generation, increased levels of FFR (Fast Frequency Response) and other reserve services are needed. This is to compensate for the absence of these traditional services coming from conventional thermal generators. Without the provision of FFR from technologies such as batteries, the Rate of Change of Frequency (RoCoF) after a system event could not be maintained within the operational standard of 1 Hz/s.

Batteries can also provide over-frequency regulation or negative reserve, helping to manage the stability of the power system in the event of large demand unexpectedly dropping off.

6.3 Power system stability

Battery storage technology, in the form of grid-forming inverters (GFI), offers rapid response to voltage disturbances and can operate during islanding and system-split events when conventional fossil fuel synchronous generation is limited. They can actively control voltage and oppose frequency imbalances, contributing to power system stability. In this form, battery storage can adjust active power to limit large changes in the system frequency and improve overall system stability. Other forms of energy storage can also provide synchronous inertia to the system.

6.4 Power quality

Battery storage technology, in the form of grid-forming inverters (GFI), can positively impact power quality by actively controlling voltage and reducing harmonic distortion caused by non-linear loads. Some GFIs have filtering capabilities to minimise harmonics in the power system. They respond rapidly to changes in demand, thus mitigating harmonic distortion due to fluctuations.

6.5 System strength and short circuit level

Grid Forming Inverters (GFI) are gaining attention as a solution to grid stability issues caused by increasing Inverter Based Resources (IBR) penetration. GFI operate like a synchronous generator, creating its own reference voltage. It potentially offers synthetic inertia to enhance transient stability, especially in weaker grid areas. Combining GFI with energy storage technologies can further improve system strength and power transfer limits. Careful deployment alongside other technologies is crucial for a successful transition to renewable energy.

Batteries with grid-forming capabilities offer stability service, enhancing inertia response and short-circuit levels beyond their core functions like energy shifting and frequency control. These capabilities can be adjusted in real-time and customised to suit grid requirements.

Batteries can compete with synchronous condensers in technology-agnostic markets for short-circuit capabilities, often offering a more cost-effective solution due to their ability to provide multiple services simultaneously. Longer-term contracts are beneficial to incentivise investments in stability services, as they can impact both capital and operating expenses.

Storage could also help lower short circuit levels in locations with already high short circuit levels – for instance, by displacing conventional plant at times of high electricity consumption.

6.6 Maintenance outages

Due to the urgency to significantly upgrade the transmission network and maintain generation plant, more maintenance outages are required in the coming years.

Maintenance outages are a significant disrupter to the reliability of the power system. Over the course of a year, hundreds (approximately 10,000[22] outage days per year) of grid components are typically taken out-of-service to allow for the energisation of new grid assets and the refurbishment or upgrade of existing equipment.

Many recent amber alert events (i.e., where there is an increased risk to security of supply) have occurred during the outage season – in situations where grid connectivity and fossil fuel generation availability is low. Generation constraint can also be significantly exacerbated in such operational conditions.

Strategically distributed long-duration storage can add the flexibility to the power system to maintain high levels of grid reliability at times of high outage concentration, by providing the traditional capability of fossil fuel generation (e.g., voltage regulation and frequency response) and minimising constraint levels.

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[22] Outage days is the sum of each outage by the outage duration

6.7 System restoration

In the event of a total or partial shutdown of the electricity transmission system, storage assets can provide black start capability by using their stored energy to start isolated or unpowered generators without external power, forming power islands that can be expanded to restore the full grid.

6.8 Virtual transmission lines

Battery virtual transmission lines are a concept where strategically placed batteries are used to manage grid congestion by temporarily storing excess energy and releasing it when demand is high, effectively increasing the capacity of existing transmission lines without physical upgrades. By placing batteries at the supply and demand ends of a congested line, surplus power can be stored and then discharged, allowing more overall energy to flow through the line than its physical capacity would normally allow under N-1 conditions. This provides a faster, more flexible, and less expensive solution to grid limitations compared to building new physical transmission infrastructure. Examples of virtual transmission are already being rolled out in countries such as Germany.[23]

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[23] https://www.energy-storage.news/fluence-building-250mw-grid-booster-battery-storage-system-for-german-tso-transnetbw/

7 Key findings of our grid study

- Even if all SOEF grid reinforcement projects are delivered, there will still be high constraint distributed throughout the power system. SOEF also does not deliver a mechanism for dealing with high levels of surplus.
- Our analysis suggests that upgrading existing assets has a clear limit. The existing topology has a capacity limit as demand grows and more renewable generation can be accommodated. Further new network connectivity is evidently required – not just the upgrading of existing assets.
- Energy storage alone is not a silver bullet but is one of the enabling technologies to allow for an increase in RES-E and reduce fossil fuel dependence.
- Under Approach A, the total constraint due to onshore wind and solar technologies in our baseline scenario is appropriately 2 TWh. The addition of energy storage at these constrained nodes helps to reduce this constraint by 30 – 50% with the longest duration energy storage options having the most impact.
- However, our analysis did show that the utility of lower duration energy storage options tends to max out sooner than the higher-duration equivalent. For instance, the 4-hour options are unavailable for more than 15% of the time when needed while the 100-hour options are unavailable less than 5% of the time. Hence our assessment of longer duration options is a conservative assessment of their ultimate capability – and showed that they have the capacity to deliver other services, for example to mitigate the high levels of surplus.
- Under Approach B, energy storage helps to lower the volume of surplus with the longest durations resulting in a greater than 3 TWh reduction in surplus.
- We also examined the impact of our energy storage portfolio on the output of fossil fuel generation. In our baseline grid model, fossil fuel generation makes up nearly 7.4 TWh of annual energy demand. All the different energy storage portfolios assessed reduce the need for fossil fuel generation – with the 8-hour energy storage portfolio reducing Ireland's fossil fuel dependence by 1 TWh and the 100-hour energy storage option reducing Ireland's fossil fuel dependence by over 2 TWh (i.e. nearly 30%). We found that while the shorter durations of energy storage result in less reductions in renewable surplus, their higher round trip efficiencies result in more fossil fuel generation displaced per unit of energy stored.
- An important outcome of our analysis is that, while energy storage helps to reduce surplus, constraint in areas of the transmission network can increase, although at a much lower level than the overall surplus reduction. This can occur at the locations where the energy storage connections have been assumed, but more so where large-scale offshore is located as more renewable energy is released to flow through the grid. So, even though energy storage minimises overall dispatch down, which is a net positive, by releasing more renewable generation it can increase loading on the grid in certain scenarios and locations. Hence, adequate grid capacity must be a requirement to maximise the impact of a large level of long-duration energy storage.
- It is also important to note that we have not carried out a complete analysis of the economic benefits of energy storage. Rather the purpose of the study is to show the potential benefits that energy storage could have in alleviating transmission network congestion, reducing renewable generation dispatch down and moving towards a more decarbonised power system. More energy storage, in addition to what we studied, could be used to mitigate renewable dispatch down even further but our portfolio of 1.8 GW of energy storage with 100 MW of different durations at each of the 18 identified nodes is only intended to be illustrative and the actual development of energy storage will be dependent on market conditions, technology availability and investment signals.
- Finally, the focus of this study has been primarily dispatch down but there are a wide range of additional services that energy storage can provide to the grid, several of which we have commented on in this report.

This is not intended to be a completely exhaustive study, rather it illustrates that energy storage can provide a range of significant benefits to the future power system.

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