Identifying the relative and combined impact and importance of a range of curtailment mitigation options on high RES-E systems in 2030 & 2040

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Executive Summary

The 2019 Irish Government Climate Action plan includes the ambitious target of increasing the installed capacity of renewable generation to meet 70% of electricity demand by 2030. High levels of curtailment will be a substantial barrier to the deployment of high levels of renewables on the Irish system. The primary objective of the study is to provide information to policy makers on the most important curtailment mitigation measures required to manage high levels of RES-E by 2030 and accelerate the development and deployment of the technical and policy focus areas required to minimise curtailment, bringing all the benefits to the Irish consumer of a low carbon energy system.

Previously there has only been limited analysis investigating the challenges of managing high RES-E in the 2030 timeline. Considering 2030 is only eleven years away, and it often takes a decade to develop electricity infrastructure projects, it is critical that all of the Irish electricity industry starts to understand and plan for an electricity system with unprecedented high levels of intermittent generation. This analysis also considered the benefits of new emerging technology that could be implemented in a 2040 timeline and assist with the challenge of transitioning to a zero-carbon energy system.

The study examined the electricity system in Ireland and seeks to determine the relative and combined impact & importance of a series of curtailment mitigation measures in making the necessary "space" for very high volumes of variable RES-E. The mitigation measures considered include reduced system conventional minimum generation limits, future interconnection, higher system non-synchronous penetration limits, higher capacity factors, diversification of technologies, demand side management and storage.

The measures proposed for a RES-E target out to 2030 would involve relatively established / proven technologies, whereas for a more ambitious RES-E target in 2040, the potential impact of technologies that have significant promise but are not yet commercially deployable at scale, such as power to gas have been explored.

The conclusions from the analysis are:

Conclusion 1

The nature of the curtailment problem at levels of renewables required to meet a 70% RES-E target are fundamentally different from today's curtailment problem. At today's levels of renewable penetration curtailment is mostly a night-time problem. The results of this analysis indicate that when trying to reach a 70% RES-E level on the Irish system, curtailment becomes an all day and in fact multi-day problem.

Conclusion 2

It is theoretically possible to get to 70% RES-E without implementing any additional curtailment mitigation measures, however it requires a massive increase in installed wind capacity and almost half of the available energy is wasted through curtailment. Without new mitigation measurements curtailment levels could reach 45%.

Conclusion 3

It is not theoretically possible to get to 70% RES-E by adding solar capacity alone. Once the installed capacity reaches a certain level, eventually all additional available energy provided by further capacity is wasted through curtailment.

Conclusion 4

Further increases in the SNSP limit will on its own have only a limited impact on curtailment. It is necessary to also address the other operational constraints that result in a minimum level of conventional generation on the system. If solutions can ultimately be found to remove all existing system operational constraints, including increasing SNSP to 100%, this could solve more than 70% of the entire curtailment problem. This is due to the fact that removing conventional generation from the system, results in space on the system that is energy unlimited. From a curtailment perspective, the space created for renewables by removing these operational constraints would be relatively “safe”.

Conclusion 5

Interconnector capacity has the potential to provide very significant curtailment mitigation benefits, however the actual curtailment mitigation performance of interconnectors will depend on the generation mix and costs of the systems to which they are connected, and likely on the future evolution of EU wholesale market design. We would strongly suggest this as an area for further study. For this reason, we would classify the modelled curtailment benefits from additional interconnector capacity in this study as being less “safe” than the benefits predicted from increasing SNSP and reducing minimum conventional generation levels.

Conclusion 6

A high fleet capacity factor has the potential to have a significant positive impact of the curtailment levels on the system. If higher capacity factor wind turbines are incentivised now, then initial modest improvements in the near term would become gradually more and more significant in the longer term as older plant is decommissioned and replaced, this could become extremely important in a 2030 - 2040 timeframe as renewable ambitions continue to increase. On this basis we would strongly recommend that DCCAE and other key stakeholders as appropriate, should consult on incorporating appropriate incentives into RESS auctions which reward renewable projects that provide a system benefit through optimised capacity factors. This should be designed such that the overall cost of energy to consumers is reduced. i.e. such that the shared benefits exceed any cost of providing the incentive.

Conclusion 7

Including solar generation in the renewable mix can help reduce overall curtailment levels. This is due to the somewhat inverse correlation between the output of wind and solar generation. For a specific set of system assumptions, the system curtailment continued to reduce until there was 10GW of installed solar capacity on the system. Depending on the relative cost of wind and solar energy, the optimal mix from a consumer cost perspective could be quite different. The curtailment improvement noted was material, but much less impactful than that seen from increasing SNSP, reducing minimum conventional generation levels and increased interconnection levels.

Conclusion 8

Energy limited storage technologies, such as batteries and pumped storage, have limited direct curtailment mitigation benefits on a high wind system. While conventional storage (battery and pumped hydro) has very little direct impact on curtailment, these technologies do have other potential system benefits that should be explored further, including providing fast frequency response, reserves, ramping and reactive power services, as an alternative to fossil fuelled peaking capacity and as a potential solution to local grid constraints.

Conclusion 9

Demand side management, including flexibility from EVs (battery electric vehicles) and heat pumps, has very limited direct curtailment mitigation benefits on systems with this high level of renewable generation. We see the direct benefits increase somewhat if applied after other more effective mitigation measures have been implemented. However, similar to storage, DSM does provide other important benefits to electricity systems with high RES-E.

Conclusion 10

By combining plausible levels of the mitigation measures, investigated in this study, it was shown that RES-E levels of 83% could be achieved while keeping average curtailment below 5%. There are however several important caveats including:

- New interconnectors were assumed to export an average of 90% of their available capacity at times of surplus renewables. As interconnector flows are currently based on wholesale electricity prices in neighbouring jurisdictions this outcome is not guaranteed. Further investigation is required to ensure that interconnectors will export near their rated capacity at times of high renewable generation in Ireland
- Removing operational constraints such that the proposed SNSP levels of 90% and min gen levels of 700MW, will require complex engineering analysis and solutions, combined with regulatory support for increased system services funding. Provided these levels can be reached the space that they create on the system is safe from a curtailment perspective, but the challenge of achieving this should not be underestimated.
- Achieving a blended wind fleet capacity factor of 38% by 2030 is likely to be quite challenging given that most of the 2020 fleet is likely to still be operational in 2030. However, with some incentives, a blended capacity factor in excess of this level for of all new wind generation post 2020 should be achievable, both onshore and offshore. As the older fleet is decommissioned and re-powered post 2030, the full system benefits of higher capacity factors are likely to be realised.
- The benefits of DSM for curtailment and RES-E are greater when they are implemented after all other measures. The earlier mitigation measures have the effect of making curtailment more of a day/night problem and in these circumstances, DSM can start to have a more meaningful impact.

Conclusion 11

The 2040 analysis indicated that in simple terms, more of the same measures can get us to a 100% RES-E system. However, over the timeframe to 2040 the uncertainties around some of these assumptions is higher. In particular, 90% exports on the interconnectors in circumstances where the entire EU market is likely also operating at very high renewable penetrations is certainly not guaranteed. At this time, it is unclear whether the technical challenges associated with completely removing operational constraints could actually be overcome.

Conclusion 12

Between 2030 & 2040 Power-to-gas or Power to hydrogen technologies appear to have the potential to help bridge that gap both by absorbing significant volumes of additional renewable power and converting it to hydrogen or green gas for use in the heat and transport sectors, but also by enabling more installed wind capacity on the system resulting in additional RES-E being dispatched to the system during times of lower / more moderate wind speeds.

To provide solutions between 2030 & 2040 knowledge of Power-to-gas, electrolyser & hydrogen technologies must be gained now. We would strongly suggest this as an area for further study.

Conclusion 13

This curtailment analysis assumes the pro-rata allocation of curtailment across wind and solar generation on an all-island basis. This is consistent with the current SEM policy and dispatch of renewable generation by the System Operators. This policy may change due to the EU new Clean Energy Package. Included in the new regulations is the removal of priority dispatch for new renewable generators. At the time of publication of this report it is not clear how these new regulations will impact, if at all, on the overall levels of curtailment of renewable generation. After the impact of the Clean Energy Package on dispatch rules for renewable generation in Ireland have been determined it may be necessary that further curtailment analysis is complete for 2030.

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Glossary

CAES: Compressed Air Energy Storage.

Capacity Factor: The wind capacity factor gives the amount of energy actually produced in a year relative to the maximum that could have been produced had the wind farm been generating at full capacity all year.

CAPEX: Capital expenditure.

CCGT: Combined Cycle Gas Turbine electricity generation, plant designed to produce electrical power from natural gas.

CHP: Combined Heat and Power, plant designed to produce both heat and electrical power from a single source.

Controllable Generator: Electricity generators that can automatically act upon a remote signal from the TSO to change it's active power output.

CSP: Concentrated solar power, a form renewable power generation.

Data Centres: Large buildings used to store data.

Demand Side Management: Involves electricity consumers having the capability to change their consumption patterns; financial incentives can result in consumers changing their consumption from high demand electricity hours where prices are high to lower priced hours which are generally night hours.

DS3: The DS3 programme is designed to securely and efficiently increase the capability of the power system with increased renewable penetration to meet policy objectives. The TSO operator (EirGrid) launched the program in 2011.

EirGrid: State-owned electricity transmission system operator in the Republic of Ireland; plans, develops and operates the electricity transmission system in the jurisdiction.

ETS: Emissions Trading Scheme; international system for trading greenhouse gases. Irish ETS sector comprises fossil fuel plants, energy intensive industries and certain specified manufacturing processes, e.g. cement manufacturing.

Non ETS: The non ETS sector is dominated by agriculture, transport, commercial businesses and households.

EV: Electric vehicle, a vehicle that incorporates a battery to power an electric motor for propulsion.

Floor Price: The lowest preconceived price that a seller will accept.

GW: Gigawatt; 1,000,000,000 watts (unit of energy).

Heat Pump: A device that provides heat energy from a source of heat to a destination called a "heat sink".

HVDC Interconnector: Connects the transmission system of one independently supplied transmission system to that of another using high voltage direct current cables.

LCOE: Levelized cost of electricity, expressed in euro/MWh; represents the average price of electricity that each type of RES-e generator would have to earn in its lifetime at a given load factor in order to cover its capital costs and operating costs.

MEC: Maximum export capacity, is the maximum capacity that a generator can export to the electricity distribution system.

Min Gen: Minimum generation level for conventional generators, a system security limit implemented by the transmission system operator.

Model: simulates the physical behaviour of a defined system with its inputs and parameters.

MVA: Mega Volt Ampere; 1,000,000 Volt Amperes. Volt Ampere is the unit used for the measurement of 'apparent power' in an electrical circuit.

MW: Megawatt; 1,000,000 Watts (unit of energy). Watt is the unit used for the measurement of 'real power' in an electrical circuit.

MWh: Megawatt hours; 1,000,000 Watt Hours. Measure of power/energy over time.

OPEX: Operational expenditure.

PLEXOS Software: PLEXOS Integrated Energy Model is a simulation software designed for energy market analysis.

PEM Electrolyser: Polymer Electrolyte Membrane electrolyser.

Power to 'X' Technologies: Energy conversion technologies that can be utilized to store surplus electricity from renewable sources. For example, Power to Gas is a technology that can convert electricity into hydrogen, which may also be converted into methane/natural gas.

PPA: Power Purchase Agreement; contractual arrangement between electricity generators and purchasers (off takers).

PSO Levy: Public Service Obligation; a government subsidy charged to all electricity consumers in Ireland. The money collected is used to subsidise renewable energy generation.

RES: Renewable Energy Source; a clean form of energy production that is harnessed from natural resources.

RES-E: renewable energy sources for electricity generation.

RoCoF: Rate of change of frequency; time derivative of the power system frequency. This quantity is of minor relevance for systems with generation mainly based on synchronous generators, because of the inertia provided to counteract load imbalances. In Ireland, this quantity has become relevant with an increasing share of Non-synchronous generators (wind, solar).

Simulation: is usually recursive; where the model is run year after year and the hypotheses and parameters can evolve over time.

SMES: Superconducting magnetic energy storage.

SNSP Limit: System Non-Synchronous Penetration; the limit imposed on asynchronous sources of electricity generation to ensure a security of supply in Ireland. Asynchronous sources include wind, solar and interconnection.

SONI: Electricity Transmission System operator for Northern Ireland; plans, develops and operates the electricity transmission system in the jurisdiction.

Synchronous Power System: Power grid where electricity is generated at a single synchronised AC frequency. All the conventional generators in Ireland run in synchronism, producing electricity at 50Hz.

System Services: Frequency control, Provision of reserve, voltage control, Load following, ability to withstand disturbances, inertia.

TSO: Transmission System Operator; responsibility of managing the bulk electricity supply in the jurisdiction.

VRES: Variable renewable sources of energy, which include wind and solar.

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1 Background

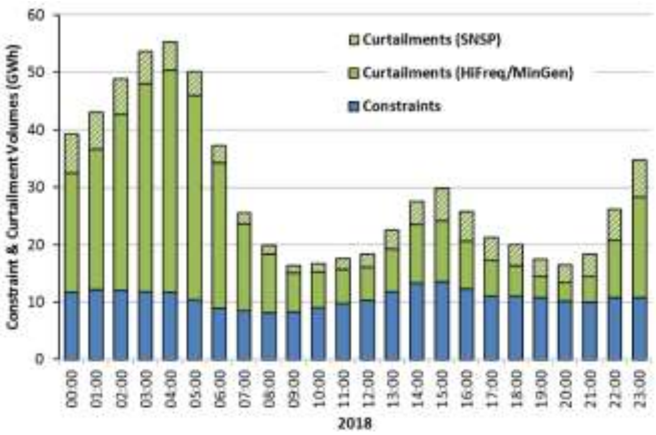
The large-scale integration of variable renewable electricity sources (VRES) into the current electricity grid is limited by a variety of technical issues that can affect reliability, affordability, sustainability, emissions and economics of the generated electricity. Several actions can be taken to mitigate the effect of intermittency and new technologies are emerging with the potential to enable a higher share of VRES into electricity/energy system. Ensuring reliability while integrating large shares of VRES can be achieved by two means:

- By incorporating technologies or actions that deal with the intermittency of the resources, namely, the geographical distribution of renewable generators over a broad region, their optimal combination taking into account their regional daily and seasonal profile and the forecasting of renewable generation.
- By incorporating flexibility into the grid to reduce the impact of intermittent generation. This includes the addition of interconnection, system stability service technologies, removal of inflexible conventional generation from the mix, energy storage, demand-side management capabilities, smart grids, Power-to-X technologies.

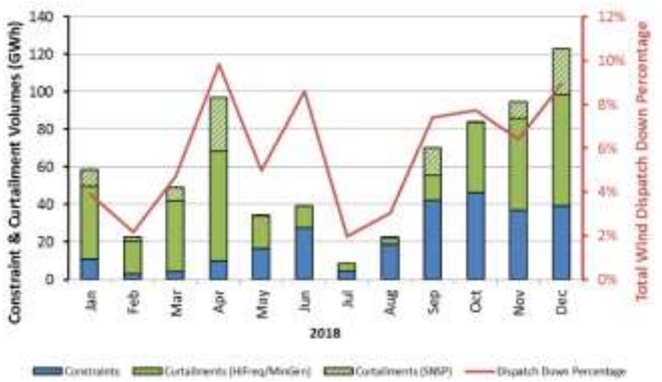
These are not mutually exclusive but complementary, and a mix of them, planned in a holistic way and taking into account local energy constraints, will be required to achieve a 100% renewable electricity supply to help decarbonise our society and combat climate change.

1.1 Curtailment

The dispatch down of renewable generation is the intentional reduction in the overall output of a renewable energy source (RES) ordered by a transmission system operator (TSO) for system security reasons. TSO's define system operational constraints that the system cannot be allowed to operate beyond without effecting system reliability / stability. Wholesale electricity markets determine the most economic mix of generation plant to run on the system in each trading period, but this schedule sometimes results in a generation mix that would cause the system to become unstable. At these times the TSO's take actions to move the system away from the market scheduled dispatch and this results in increases in wholesale generation costs (known in Ireland as dispatch balancing costs). Curtailment of renewables is said to occur when this re-dispatching of renewables is the result of system wide limits being exceeded. When this re-dispatch occurs due to a local issue (e.g. insufficient capacity on the local transmission lines) it is known as constraint.



(a)



(b)

Figure 1 All-Island breakdown of wind constraints and curtailments in 2018 (a) hour of day (b) monthly [1].

Operational constraints currently imposed by the TSO include the system non-synchronous penetration (SNSP) limits, system inertia and rate of change of frequency (RoCoF) limitations and the minimum number of conventional generators that must be maintained on the system (Min Gen). Figure 2 illustrates how in 2018 the curtailment was split across these three limitations.

It should be noted that these limits are set based on the physical capabilities of the system as it exists at a point in time, along with the operational and control capabilities of the TSO. As the system and capabilities evolve, it is possible to maintain system stability while allowing more non-synchronous renewable generation to run. Ensuring the positive evolution of the system in this regard is at the core of EirGrid's world leading DS3 program.

Curtailment and constraint restrict zero carbon electricity entering the grid and effectively wastes zero marginal cost electricity that could otherwise be used. The lower the value of constraint and curtailment should generally lower the cost of electricity and lower the carbon footprint of the energy system.

Table 1 Installed wind capacity and curtailments 2011-2018 [1].

Republic of Ireland 2011-2018			
Year	Wind Capacity (MW)	Annual (All Island) Wind Capacity Factor %	Wind Curtailment %
2011	1585	31%	2.0%
2012	1703	28%	1.5%
2013	1923	29%	2.5%
2014	2266	28%	2.9%
2015	2447	32%	3.3%
2016	2779	27%	1.4%
2017	3314	27%	2.6%
2018	3666	28%	3.3%

Wind energy has grown significantly in Ireland since 1990, the International Energy Agency (IEA) Wind Task 25 [2] states that from experience wind curtailments do not occur for small shares 5-10 % of renewables of yearly electricity consumption. As Ireland has sought to achieve deep de-carbonisation of its electricity system, the higher shares of wind on the system have presented technical challenges for the TSO.

Table 1 above illustrates the ROI curtailment levels between 2011 and 2018 [1], where it has been generally increasing, mainly due to installed wind capacity increasing each year. However, there were decreases in curtailment in both 2012 and 2016, with the main reason appearing to be decreases in wind capacity factor for each year compared to the preceding years.

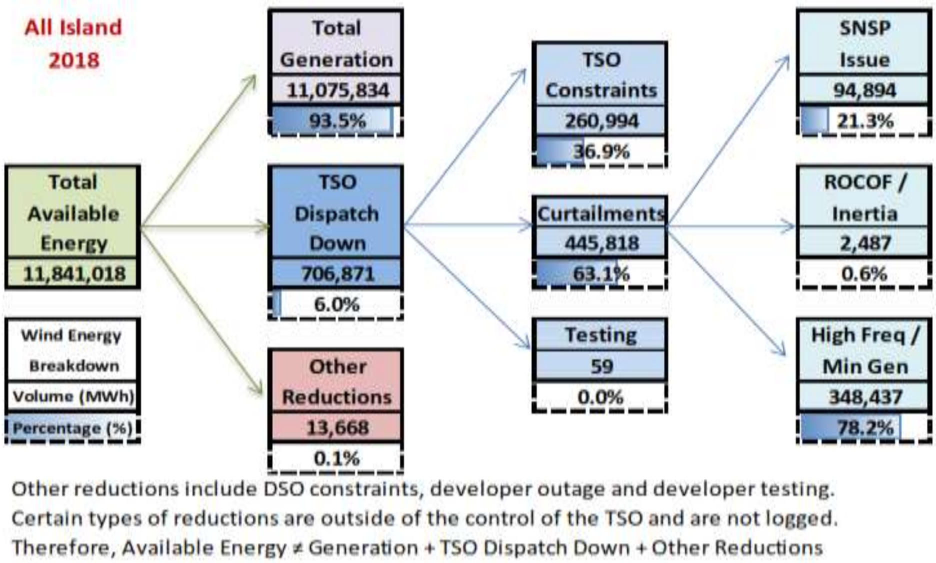


Figure 2 Wind dispatch-down Categories 2018 [1].

2 WP 1 Literary Review

2.1 Introduction

The European Union (EU) has taken major steps towards reducing carbon emissions from fossil fuel use in an effort to tackle climate change. Binding targets set out in the Renewable Energy Directive (RED) 2009/28/EC for Ireland in 2020 include zero carbon renewables accounting for 16% of the national energy consumption, a 20% reduction on greenhouse gas (GHG) emissions based on 2005 levels and a 20% efficiency improvement based on the energy use between 2000 & 2005. In its National Renewable Energy Action Plan Ireland proposed to meet its 16% Renewable energy target by implementing a 40% share of renewable electricity, 12% share of renewable energy in the heat sector and 10% of renewable energy supplying the transport sector [3]. In addition, the Department of Communications, Climate Action and Environment (DCCAE) in the 2015 Energy White Paper set a specific target of reducing Irelands greenhouse gas (GHG) emissions by 85% to 90% compared to 1990 levels by 2050 [4].

The EU's Clean Energy Package commits the EU members to increase RES share from 20% in 2020 to 32% by 2030. In Ireland's 2019 Climate Action Plan the renewable energy target for electricity was set at 70% by 2030 [5]. The Government plan expects this new target to require the addition of 9GW of renewable energy capacity. The plan sets out detailed actions in the areas of onshore and offshore wind, solar generation, interconnection and measures to manage the planned high levels of renewables on the electricity system.

2.2 Approach to Energy up to 2030

The energy policy employed by the Irish government targets three core objectives often referred to as 'energy pillars'. The objectives are; competitiveness, security of supply and sustainability. Renewable energy sources for electricity (RES-E) are becoming increasingly important for Irelands energy supply. In 2005, renewable generation accounted for 6.8% of Ireland's gross electricity consumption, while normalised renewable generation accounted for 30% of Ireland's gross electricity consumption in 2017 with the majority of this being provided by onshore wind [6].

2.3 Demand

Demand in the Irish electricity system is forecast to increase significantly in the coming decade, due to increased numbers of datacentres connected to the grid as well as the increased number of electric vehicles (EVs) and heat-pumps to be installed into homes and businesses [7][8].

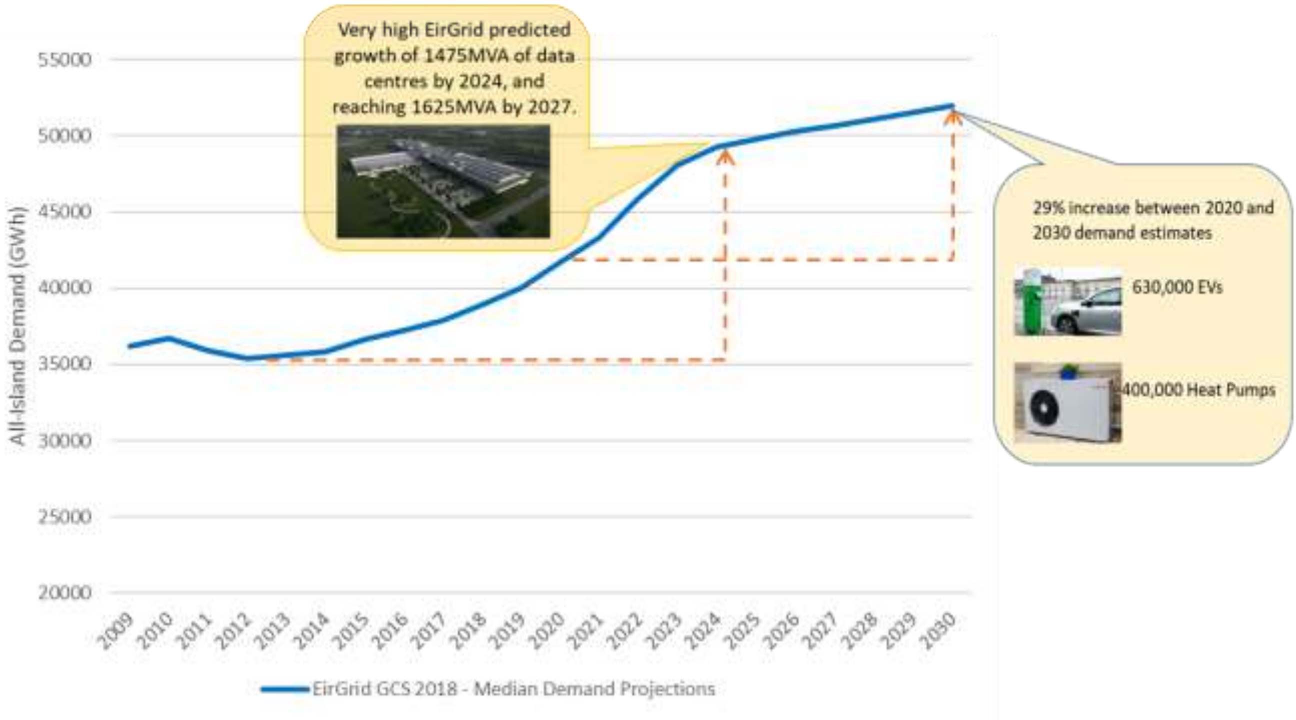


Figure 3 Demand between increase assumptions [7][8].

2.4 Conventional Generation - Coal and Peat Decline

Looking forward to 2030 all of the scenarios from EirGrid's Tomorrow's Energy Scenarios publication [9] estimate a decline in fossil fuel generation between 2020 and 2025 arising from increasing carbon prices and EU emissions directives. Coal and peat generation are assumed to cease by 2025 in the low carbon living scenario. The conventional generation portfolio is predicted to be primarily gas-fired by 2030. Heavy fuel oil ceases by 2025 resulting from the expected decommissioning of Tarbert power station in 2023, while distillate oil generation also sees a decline between 2020 and 2030 where some plants are converted to gas.

2.5 Renewables – Wind & Solar Increase

Wind energy is an abundant natural resource on the island of Ireland with some of the highest wind speeds in Europe. Renewable generation capacity continues to grow in all EirGrid's Tomorrow's Energy Scenarios 2017. Onshore wind remains the largest contributor between 2020 and 2030. However, in the low carbon living scenario, alternative renewable sources become more prominent in 2025 and 2030. Offshore wind may account for up to 25% of renewable capacity by 2030 in the high renewable scenario where RES are connected at a large scale to the transmission/distribution system. Solar PV capacity grows due to decreasing capital costs between 2025 and 2030. In Ireland's 2019 Climate Action Plan, onshore wind energy is expected to reach 8,000MW by 2030, and there would be at least 3,500MW of offshore wind and up to 1,500 MW of solar generation.

However, wind and solar is variable with weather conditions not always matching electricity demand, at times producing too much energy in low demand periods and less energy in peak demand periods, in addition there is a seasonal variation of wind across summer and winter. Figure 4 presents time series data which provides a compelling visualization of renewable energy's intermittent correlation with demand.

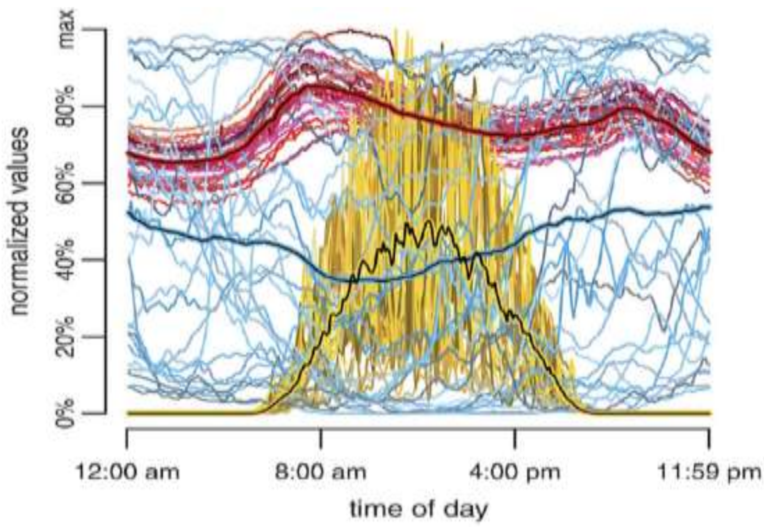


Figure 4 Wind-power generation (blue), solar (gold), and power demand (red), average values are in colour-highlighted black lines (thirty days of data collected in April 2010) [10].

2.6 System Operation with High Levels of Renewable Generation

Operating electricity systems with high levels of variable non-synchronous renewable generation brings new challenges to TSO's. TSO's have to consider multiple operational constraints to maintain system security. In Ireland, the most well-known of these operating constraints to facilitate high renewable generation is the SNSP limit which provides for a maximum percentage of non-synchronous generation (including any DC imports), when compared with demand + DC exports. This limit is currently being operated at 65%. This system constraint may be described by Equation 1 below.

$$SNSP = \frac{wind\ generation + HVDC\ imports}{system\ demand + HVDC\ exports}$$

Equation 1 SNSP Limit for Ireland.

As can be seen from EirGrid's published operational constraints list, there are a variety of system constraints applied, which result in a certain minimum amount of conventional generation required on the system at all times to maintain system voltage and stability [11]. This "must-run fossil fuel generation" combined with the "SNSP limit" removes "space" within which variable renewables could otherwise meet demand. Interconnection can increase system space when exporting or decrease system space when importing. When the amount of variable renewable generation exceeds this available system space, the TSO is required to dispatch down renewable generation to maintain the system frequency at 50Hz while balancing supply and demand. This is known as curtailment and even at current levels of renewable penetration this is starting to emerge more on the system with Republic of Ireland (ROI) wind curtailment reaching 3.3% in 2018 [1].

Frequency and dynamic stability issues at high instantaneous penetrations of wind power were identified in the TSO Facilitation of Renewables Study [12]. It was estimated that transient stability issues can be mitigated for the anticipated level of non-synchronous generation planned to connect to the system to meet the 2020 40% RES-E targets. Frequency stability was the greatest concern. The SNSP limit was introduced to constrain the instantaneous penetration of non-synchronous sources. It is planned that the SNSP limit will reach 75% in 2020 so as Ireland can achieve higher shares of electricity generated from RES-E without excessive curtailment.

There have been a range of academic studies examining renewable energy pathways that apply these existing and proposed 2020 constraints, many of which identify curtailment as a limiting factor / challenge in growing Ireland's renewable electricity sector [13][14]. However, we are not aware of any significant body of work in a 2030 timeframe that looks at the range of potential curtailment mitigation measures available in Ireland and examines, in a methodical fashion, the relative effectiveness of these measures. In not considering the effectiveness of potential curtailment mitigation measures, it is possible that some of these studies may be under-estimating the potential of variable renewable electricity to contribute to future renewable energy targets.

To add some additional context to this point, in March 2016 EirGrid published a paper entitled "RoCoF Alternative & Complementary Solutions Project – Phase 2 Study Report" [15]. This report highlighted that there are other technologies available that can assist with system stability while reducing the need to constrain on existing conventional plant. This begs the question, if these solutions were to be implemented such that SNSP could be further increased and conventional minimum generation constraints were to be reduced, what effect would this have on curtailment in a very high RES-E Irish electricity system. While our proposed study will not address the dynamic electrical issues associated with alternative solutions to operational constraints, what it will seek to answer is how important would these solutions be at RES-E penetration levels across a range including the Climate Action Plan's 70% RES-E target for 2030.

2.7 Curtailment Mitigation Measures - SNSP

Following EirGrid's Facilitation of Renewable Studies in 2010, the SNSP limit was initially set at 50%. EirGrid's DS3 Project [16] was launched to increase the SNSP limit to 75% by 2020. The DS3 project requires changes to generators, new tools and practices within the EirGrid and SONI control centres and the increased provision of existing and new ancillary system services. In 2019 the SNSP limit is currently at 65%. EirGrid are also leading a European wide study called EU-SysFlex [17] which is investigating the potential for a high penetration of renewable generation across Europe by 2030.

2.8 Curtailment Mitigation Measures - Minimum Conventional Generation

Reducing minimum conventional generation levels is another means of increasing space on the system for renewable generation, and as a result reducing curtailment. EirGrid and SONI have indicated in their 2013 and 2016 Constraint Reports respectively [18][19] that the level of minimum conventional generation required could reduce in the coming years due to system upgrades that remove voltage stability issues, new interconnection between the Ireland and Northern Ireland systems, increasing system RoCoF levels and the increased provision of ancillary system services from existing and new service providers.

2.9 Curtailment Mitigation Measures - Interconnection

Interconnection is expected to be a key mitigation, assuming that interconnectors are exporting energy. In addition to the existing East West (EWIC) and Moyle interconnectors, there are currently two proposed interconnectors which are designated as Projects of Common Interest (PCI). EirGrid and RTE (French TSO) are proposing a 700MW interconnector, called the Celtic Interconnector, to link the transmission grids in Ireland and France, and is expected to go live in 2025/26 [20]. The Greenlink Interconnector is being developed by a private entity and is proposed to link the transmission grids in Ireland and Wales with a 500MW capacity [21].

2.10 Curtailment Mitigation Measures - Energy Storage Technologies

Grid storage solutions can help to avoid RES curtailment (see appendix for summary of storage technologies). Utility-scale storage solutions allow the operators to shift the supply when it better matches the load. Also, it is possible to provide ancillary services with storage solutions. Behind-the-meter storage coupled with local solar PV systems allow a better use of the energy provided to the grid, in particular, when time-of-use tariffs are provided by the DSO. Thermal energy storage also allows shifting renewable electricity as heating and cooling demand for several applications can be moved in time. Pumped storage (hydropower) is well established and is the most significant source of electricity storage globally, but other storage technologies are becoming cost-effective in some applications.

Grid storage solutions are at different maturity levels, from research to technology demonstration and then in-market applications. Solutions are generically classified by the amount of energy they can store and how quickly it is possible to store (charge) and/or release (discharge) the energy. Some storage solutions are briefly commented on as follows:

- Pumped hydro: it consists of pumping water downstream to upstream when VRES surplus exists. In this case, the energy is stored as gravitational potential energy. The economic benefits of these projects depend on local geographical considerations, as the investment cost and payback time depends on the capacity of local reservoirs and if the reservoir has to be built or enlarged. It is a fully mature technology, e.g. Turlough Hill pumped storage plant in Ireland.
- Batteries (centralized and decentralized): persisting cost-reduction of battery storage is driving this technology very fast into the grid, though most commercial applications to date relate to provision of fast acting reserves supporting frequency stability and management of demand side network constraints. There are different types of battery technologies, with Lithium-ion and lead acid batteries being the most popular cost-effective solutions in the market. Battery storage life cycle assessment, second life and capacity are still issues.
- Flywheels: energy is stored as kinetic energy in high velocity rotating disks. The technology is at a demonstration stage and one of its main features is providing a high discharge rate.
- Hydrogen: can be produced by VRE electricity and thus providing storage as a fuel. Hydrogen is now becoming a reality in the market, after demonstration projects across Europe, Asia & US have provided confidence in the technology.
- Compressed Air Energy Storage (CAES): as its name indicates, energy is stored in compressed air. The different technologies in this category can be classified by the thermal cycle they use.
- Synthetic gas storage (methane with high energy and power densities) conventionally used for natural gas: synthetic (or substitute) natural gas can be produced from VRES surplus by water electrolysis to produce hydrogen and then combining it with carbon dioxide to produce methane which can also be injected into the grid (and water as a by-product). The goal is that it can be combined with Carbon Capture technologies so that it provides both RES storage and decarbonisation by means of capturing carbon dioxide.
- Superconducting Magnetic Energy Storage (SMES): in this case, the energy is stored in the magnetic field of high current loops. Superconductivity is a requirement for reducing Ohm losses.

- Other technologies can be found, such as Liquid Air Energy Storage (LAES), Latent Heat thermal storage (Phase Change Material or others) and other thermal storage, such as molten salt energy storage used in Concentrating Solar Power plants, among others.

2.11 Approach to Energy 2030 - 2040

In a deep decarbonising world, offshore wind coupled with solar capacity may grow in huge proportions in the 2030's & 2040's as their cost reduces in the 2020's and 2030's. However, this would only happen if storage technologies, such as Power-to-Gas are mature enough to accommodate the expansion and are cost effective to mitigate the cost of very high curtailment rates.

The "**Renewable Electricity Curtailment Model**" developed for this project, can incorporate what happens outside the electricity grid such as storage and power to gas capability. Power-to-gas can produce renewable gas, either hydrogen directly or be used to produce bio-methane/methane. By 2040 it is envisioned that the natural gas grid will continue to be decarbonised, using renewable gases; bio-methane from waste and hydrogen from Power-to-gas, both injected to the gas grid [22][23]. Renewable gases can therefore assist in reducing CO2 emissions in heating and transport sectors as well as the combined cycle gas turbine (CCGT) electrical generation in Ireland.

Figure 5 Transition from high carbon to zero carbon gas grid enabled by bio/methane & Power-to-Gas Storage.

2.12 Curtailment Mitigation Measures - Hydrogen & Power-to-Gas

Sector coupling is the integration of power, heat and fuels supply, via their joint use, conversion or substitution for meeting industry, transport and residential demands. Power-to-X refers to the sector coupling technology in which electricity, in particular VRES electricity surplus, can be used for demands that were traditionally supplied by other energy resources. These solutions, if intelligently planned and deployed to coincide with off-peak periods in demand, have the potential to open new market applications for VRES that are currently not accessible.

The most important Power-to-X technologies are Power-to-Gas, Power-to-Mobility and Power-to-Heat. Power-to-Gas solutions include the production of hydrogen or other gases for their later use in the electricity, transport, gas-grid injection (towards heating) or industry sectors. It enables also the time and space shift of the supply via storage and transportation of the fuels.

Power-to-Mobility involves electric vehicle (EV) supply via electricity grids and charger networks. EVs are potentially flexible loads that can be demand or supply depending on whether their batteries are charging or discharging. Again, intelligent charging strategies are required to avoid peak loads that stress the grid. In such cases, EVs are a potential flexible demand to enhance the increase of VRES in the electricity grids as their demand can be shifted to align with the VRE generation profile. Finally, Power-to-Heat strategies refer to the electricity use in the industrial or residential sector for heating or cooling by using heat pumps/refrigerators or direct heating. The thermal storage for residential water heating or district heating along with heat pumps are a potential flexible load that can help the VRES deployment, again, if intelligently managed via time-of-use tariff or similar.

3 WP-2 Develop and Calibrate Curtailment Model

3.1 Modelling Approach

Energy systems modelling tools are time consuming to construct, and therefore it is not feasible to create new tools for every analysis, hence if suitable and accessible models exist, these should be utilized. However, difficulty exists when identifying the most appropriate modelling tool for investigations into the potential of renewable energy growth. Currently there is no set structure for typology of energy modelling tools, but in recent times academics/researchers have focused on classifying energy systems models by various criteria. Numerous papers from academics regarding modelling tools for electricity systems and energy systems may be accessed from the literature [13][14], for example Connolly et al. [24] reviewed 37 computer tools used to analyse the integration of renewable energy into various energy systems. He concluded that the MARKAL/TIMES model was identified as a popular choice and had been used in 70 countries and 250 institutions at the time of this analyses. However notable disadvantages of utilizing this model for this project are that it is a highly complex model with long computational times and requires the user to enter certain physical constraints before performing an optimisation run. If some of these constraints were to be removed the optimisation model would produce a different result.

Given the complexity of the model, it is more difficult to conduct a significant multi-scenario analysis to answer a huge number of "what if" questions relating to system constraints and other mitigation options. PLEXOS is another commonly used model designed specifically to optimise hourly generation dispatch on the electrical system. This is also a highly complex model with long computational times, where much of the computational power is being used to determine the optimal mix of conventional generation to balance the system. When trying to understand the drivers of renewable curtailment along with potential mitigation measures this level of complexity is not necessarily required.

3.2 Renewable Electricity Curtailment Model

The "Renewable Electricity Curtailment Model" used in this study was developed by Paul Blount and supported by Mullan Grid consulting over the past 2.5 years and refined for this study. Given it is an excel spreadsheet-based model as opposed to a full PLEXOS unit commitment model, it becomes easier to conduct a significant multi-scenario analysis to identify key trends and relationships between various system parameters. The "Renewable Electricity Curtailment Model" allows any hourly demand, wind and solar profile to be entered and scaled. In addition, up to 10 balancing technologies can be entered including conventional generation, storage technologies and interconnectors and may be dispatched in different priority orders in charging/ export and discharging/ import modes. Minimum conventional generation levels can be entered for each balancing technology as required and the SNSP limits set. The model compares available wind and solar and minimum conventional generation with demand for each hour, where there is a surplus or shortfall it dispatches the balancing technology based on a user selected dispatch priority.

In the case of storage technologies, the available MWh capacity is checked and then it moves onto the next technology when the storage technologies become full or empty as appropriate. Finally, the SNSP limit is applied and wind and solar technologies are curtailed where there are exceedances and generation from other balancing technologies is increased as required. This "Renewable Electricity Curtailment Model" allows storage technologies, many different renewable technologies and interconnectors to be added, manipulated and scaled, incorporating efficiency, capacity factors and cost parameters. The model and more precisely the results can interact with MATLAB to produce the final graphs or animated results.

The advantage of a spreadsheet (excel) based model is that it is low cost to setup, and the programming is not complex to learn or interpret. It can be easily checked against other similar models and can be open sourced, which also points towards the limitations of the model. Some of the limitations include the model was not designed to model market pricing and therefore can only model idealised operation of storage & interconnection for example. Similar to most models 'perfect foresight' nature of the wind and solar profiles is applied which can lead to discrepancies in comparison to what might be experienced in real-time operation. These limitations have been reduced by applying key input assumptions and tested and calibrating to have high confidence in the results.

With regards to the input assumptions applied to this project, EirGrid's All-Island Generation Capacity Statement 2018 – 2027 [7] was a key reference document, particularly in terms of electricity demand and renewable generation. Assumptions relating to electricity vehicles and heat pumps were obtained from a report commissioned by IWEA entitled "70 by 30 – A 70% Renewable Electricity Vision for Ireland in 2030" [8], while EirGrid's Tomorrow's Energy Scenarios 2017 [9] was referred to in terms of data centre electricity demand.

The curtailment model assumes the pro-rata allocation of curtailment across wind and solar generation on an all-island basis. This is consistent with the current SEM policy and dispatch of renewable generation by the System Operators. This policy may change due to the EU new Clean Energy Package. Included in the new regulations is the removal of priority dispatch for new renewable generation. At the time of publication of this report it is not clear how these new regulations will impact, if at all, on the overall levels of curtailment of renewable generation. It does appear likely that it will impact on how curtailment is allocated between renewable generators. After the impact of the Clean Energy Package on dispatch rules for renewable generation in Ireland have been determined it is recommended that further curtailment analysis in complete for 2030.

3.3 Renewable Electricity Curtailment Model Calibration

The Renewable Electricity Curtailment Model used for this study was calibrated against EirGrid's curtailment levels from their Annual Renewable Energy Constraint and Curtailment Report for 2015. A calibration exercise was designed for the purpose of this study. Key input assumptions were made in relation to generation, demand, interconnection and system constraints in order to calculate curtailment for 2015.

Hourly profiles for 2015 for actual wind availability and actual demand sourced from EirGrid were used for this exercise (Demand: ROI = 26,625GWh and NI = 8,786GWh). A 2013 non-wind renewable generation profile received from the CER was modified to represent 2015. The original profile received varied between weekdays and weekends, the first day of the year in 2013 was a Tuesday and a Thursday in 2015 – therefore the first Thursday on the 2013 profile was used for the start point of the modified 2015 profile and the two preceding days being moved to the 30th and 31st of December.

Installed capacities for generation and interconnection were referenced from the EirGrid All-Island generation capacity statement 2015-2024. Information on controllable wind generators in the ROI and NI came from Mullan Grid Consulting's in house database which is updated whenever EirGrid, ESBN, SONI and NIE provide connection statistics. Mullan Grid Consulting analysed curtailment events on both the EWIC and Moyle Interconnector in 2015, from the analysis an average available export capacity of 47MW was considered.

Two system parameters were considered for the exercise which are System Non-Synchronous Penetration (SNSP) level and the Minimum level of Conventional generation. The SNSP limit was at 50% up until the end of the 15th of October 2015, after which it was increased to 55%. Minimum conventional generation levels were based on additional analysis performed by *Mullan Grid Consulting* on the operation of must run plants during curtailment events in 2015. Results indicate that the developed Renewable Electricity Curtailment Model matched the EirGrid Annual Renewable Energy Constraint and Curtailment Report for 2015 to within 0.1%.

Table 2 Calibration Input Assumptions (All Island)

Renewables Installed capacity	All Island (MW)			
Wind	3162			
Solar	1			
Biomass	0			
Uncontrollable Wind	577			
Uncontrollable Solar	0			
Balancing Technologies Installed Capacity	**Charging/ Exporting) (MW)**	**Discharging/ Importing (MW)**	**Eff (%)**	**MWh**
Idealised Interconnectors	0	0	100%	1.00E+26
Existing Pumped Hydro	219	219	80%	1314
New Pumped Hydro	0	0	80%	0
Batteries	0	0	80%	0
Biomass	0	100	100%	1.00E+26
Conventional Generation	0	9000	100%	1.00E+26
Hydrogen PtG	0	0	60%	1.00E+26
System Parameters				
SNSP Limit		50%		
Conventional Min Generation		1750	MW	
Biomass Min Generation		0	MW	
Total Min Generation		1750	MW	

ROI Installed Wind: 2,022MW controllable and 430 MW uncontrollable – figures obtained from Mullan Grid's inhouse database, which is updated whenever EirGrid, ESBN, SONI and NIE provide connection statistics.
NI Installed Wind: 563 MW controllable and 147 MW uncontrollable – figures obtained from Mullan Grid's inhouse database, which is updated whenever EirGrid, ESBN, SONI and NIE provide connection statistics.
Wind Profiles: Based on EirGrid & SONI's 9 regional 2008 wind profiles which have an overall capacity factor of 31.7% which is in line with the 13-year average according to EirGrid/SONI's 2016 Generation Capacity Statement.
SNSP Limit: EirGrid commenced the 55% trial on 16th October 2015. Therefore, up to this date 50% SNSP is applied, rising to 55% after.
Min Gen: 1280MW in ROI and 470MW in NI – Mullan Grid provided figures by reviewing the operation of must run plants during curtailment events in 2015. Data sourced from SEMO website.
Interconnection: Assumed neutral flows on both EWIC and MOYLE.
Storage: Based on information provided by EirGrid on Turlough Hill, it is assumed that 3 of the 4 pumps run on an energy arbitrage basis with 219MW available to mitigate curtailment, with 6h discharge capacity when full.

Table 3 Calibration Results (All Island)

Renewables Data				
RES-E %		29.7%		
Curtailment Data		**Calculated Value**		**EirGrid Value**
Total Wind Curtailment		**3.2%**		**3.3%**
Controllable Wind Curtailment		3.9%		
Number of Curtailment events		147	No.	
Total Hours of Curtailment		713	hrs	
Average Duration of Curtailment event		4.9	hrs	
Maximum Duration of Curtailment event		14	hrs	
Check Energy Balance		**(MWh)**	**%**	**Notes**
Total Demand		35,411,283	100.00%	
Available Wind		8,772,554	24.77%	RES-E Local
Wind Curtailment	-	279,594	-0.79%	RES-E Local
Available Solar		880	0.00%	RES-E Local
Solar Curtailment	-	2	0.00%	RES-E Local
Storage technology losses	-	35,833	-0.10%	RES-E Local
Waste and hydro		1,300,597	3.67%	RES-E Local
Biomass		773,947	2.19%	RES-E Local
IC Exports		-	0.00%	RES-E Exports
1. Total RES-E used locally		10,532,548	29.74%	RES-E Local
Add RES-E Exports		-	0.00%	RES-E Exports
Total RES-E		10,532,548	29.74%	RES-E Total
Balance of local Demand from:				
2. IC Imports + Conventional		24,878,735	70.26%	
3. Emergency Load Shedding		-	0.00%	
Local Demand met by 1 + 2 + 3		35,411,283	100.00%	
Energy Balance error		0.00000000%		

4 Project Aims & Objectives

This study will examine the electricity system in Ireland and seek to determine the relative and combined impact & importance of a series of curtailment mitigation measures in making the necessary "space" for very high volumes of variable RES-E. The mitigation measures to be considered include higher system non-synchronous penetration limits, reduced conventional minimum generation limits, further interconnection, higher capacity factors, diversification of technologies, demand side management and storage.

The measures proposed for a RES-E target out to 2030 would involve relatively established / proven technologies, whereas for a more ambitious RES-E target in 2040, the potential impact of technologies that have significant promise but are not yet commercially deployable at scale, such as power to gas will be explored.

We would envisage this as being an early body of work to help identify key focus areas for future detailed studies and analysis. A section on recommendations for policy makers and regulators along with suggestions for prioritisation of further research is included. The detailed aims and objectives of the study agreed with SEAI include:

- Review existing approaches to curtailment modelling and mitigation measures to reduce curtailment in 2030 and 2040 timelines.
- Further develop, calibrate and test our existing curtailment model to incorporate additional functionality to model the integration of flexible heat and transport demand.
- Develop base case scenario of 70% RES-E in 2030 without any new curtailment mitigation measures, determining the amount of installed wind capacity that would be required and the expected curtailment.
- Using a comprehensive multi scenario analysis, produce graphical representations of the relative effectiveness of a broad range of mitigation options, including SNSP increases, minimum conventional generation constraint reductions, capacity factor increases, diversification of technologies, addition of interconnectors, and varying types & durations of storage and demand flexibility measures (the effect on both required RES-E capacity and curtailment at 70% RES-E would be determined in all cases). An assessment of a higher RES 2040 scenario incorporating emerging technologies including power to gas would also be provided.
- From results of analysis determine a series of feasible 2030 scenarios with 70% RES-E, that could be considered in future detailed PLEXOS and / or TIMES studies.
- Produce an animation of a selection of the 2030 scenarios to allow public understanding of the how the power system in 2030 may have to look and operate with 70% RES-E.
- Provide a project report aimed at informing policy makers and stakeholders.
- Dissemination of key findings to policy makers and stakeholders to communicate the curtailment challenge and opportunities from 70% RES in 2030.

5 WP3 – WP 11 Analysis/Results

5.1 WP-3 Develop Base Case Scenario for Wind

In this work package we modelled 2030 demand and a central estimate of the 2030 wind fleet capacity factor of 34% but retained all other 2020 system assumptions. These are outlined in detail in Table 4 below. The "idealised" interconnector capacity modelled considered current export limitations on the Moyle interconnector as well as assuming relatively high export levels on the interconnectors during times of high wind on the Irish system. We then attempted to reach 70% RES-E system by adding additional wind capacity without changing anything else on the 2020 system. A central demand estimate incorporating background demand growth, datacentre, heat and transport growth was established and used for all scenarios and work packages. No demand flexibility is considered in this work package. This was intended to effectively demonstrate the extent to which the system "breaks" if variable renewable generation is added in the absence of other measures. The end point of this work package (70% RES-E at very high curtailment levels) is then used as the starting point for the analysis in WP4-8 in which a series of curtailment mitigation strategies are assessed.

Table 4 Input Assumptions for WP 3 (All Island)

Renewables Installed capacity		All Island (MW)	C.F. avail %	
Total Wind		5597	33.96%	
Total Solar		323	10.0%	
Uncontrollable Wind		751		
Uncontrollable Solar		166		
Balancing Technologies Installed Capacity	MW (charging / Exporting)	MW (Discharging / Importing)	Eff (%)*	MWh
Idealised Interconnectors	380	380	100%	1.00E+26
Existing Pumped Hydro	219	219	80%	1314
New Pumped Hydro	0	0	80%	0
Batteries	0	0	80%	0
Conventional Generation	0	9000 **	100%	1.00E+26
Hydrogen PtG	0	0	60%	1.00E+26
System Parameters				
SNSP Limit		75%		
Conventional Minimum Generation		1400	MW	
Demand				
Total Demand		53,838,465	MWh	
% increase in 2015 Baseline (RoI)		10.92%		
% increase in 2015 Baseline (NI)		10.36%		
Additional datacentres above 2015		1591.25	MW	
Number of electric vehicles added to baseline		629,398	No.	
Number of heat pumps added to baseline		396,302	No.	
Average Cylinder Size in heat pump system		500	litres	
Maximum water temperature		55	deg C	
Minimum water temperature		25	deg C	
Ambient house temperature		22	deg C	
% of flexible background demand		0%		
% of flexible data centre demand		0%		
% of flexible EV demand		0%		
Utilise storage capacity of heat		FALSE		

(*) These are conversion efficiencies for storage technologies. 100% is used for conventional generation as the energy provided from conventional generators is not subsequently converted or stored, it simply fills gaps when there is insufficient renewable generation. For hydrogen PtG the efficiency figure used is the for conversion from PtG only.

Where PtG is deployed in this study it is assumed that the gas is used in the heat and transport sectors and isn't converted back to electricity.
(**) It is important to note that assessing capacity adequacy didn't form part of this study. For conventional technologies we simply included a very large amount of conventional's in the model such that demand was always met. We would note however that the capacity adequacy requirement can be met through additional interconnection and batteries in addition to conventional generation capacity, and on high RES-E systems there is also a capacity contribution from renewables on the system.

The results of this WP3 analysis are summarised in the tables and figures below. Key conclusions / observations were:

- It is theoretically possible to get to 70% RES-E without implementing any additional curtailment mitigation measures, however it requires a massive increase in installed wind capacity and almost half of the available energy is wasted through curtailment. Without new mitigation measurements controllable wind curtailment levels could reach 45%.
- The nature of the curtailment problem that we need to solve is fundamentally different at this level of renewable penetration. At today's levels of renewable penetration curtailment is mostly a night-time problem. The results of this analysis indicate that when trying to reach a 70% RES-E level on the Irish system, curtailment becomes an all day and in fact multi-day problem. Table 5 illustrates that at 70% RES-E, the average duration of discrete curtailment events was 29.4 hrs, the maximum event duration was 206.0 hrs and in total there were 5,404hrs in the year during which curtailment was taking place, equivalent to 61% of the entire year.

Table 5 Wind installed capacity increase vs RES-E and Curtailment

			Total Curtailment		Controllable Curtailment					
Scenario	Wind IC (MW)	RES-E (%)	Wind (%)	Solar (%)	Wind (%)	Solar (%)	Events (no.)	Average Duration (hrs)	Maximum Duration (hrs)	Total hrs of curtailment events (hrs)
1	5597	34.6%	0.1%	0.0%	0.2%	0.0%	26	3.3	7.0	87
2	6000	36.8%	0.3%	0.0%	0.4%	0.0%	41	3.8	10.0	156
3	8000	46.3%	3.7%	0.4%	4.1%	0.9%	150	6.6	23.0	985
4	10000	53.1%	10.6%	2.0%	11.4%	4.0%	185	11.4	63.0	2104
5	12000	58.0%	18.0%	3.8%	19.2%	7.8%	224	13.3	83.0	2978
6	14000	61.8%	24.9%	5.7%	26.3%	11.7%	223	16.7	95.0	3721
7	16000	64.7%	30.9%	7.5%	32.4%	15.4%	223	19.3	131.0	4302
8	18000	67.0%	36.2%	9.2%	37.8%	19.0%	215	22.3	188.0	4792
9	20000	69.0%	40.9%	10.9%	42.5%	22.4%	199	26.0	199.0	5176
10	21200	70.0%	43.4%	11.8%	44.9%	24.3%	184	29.4	206.0	5404

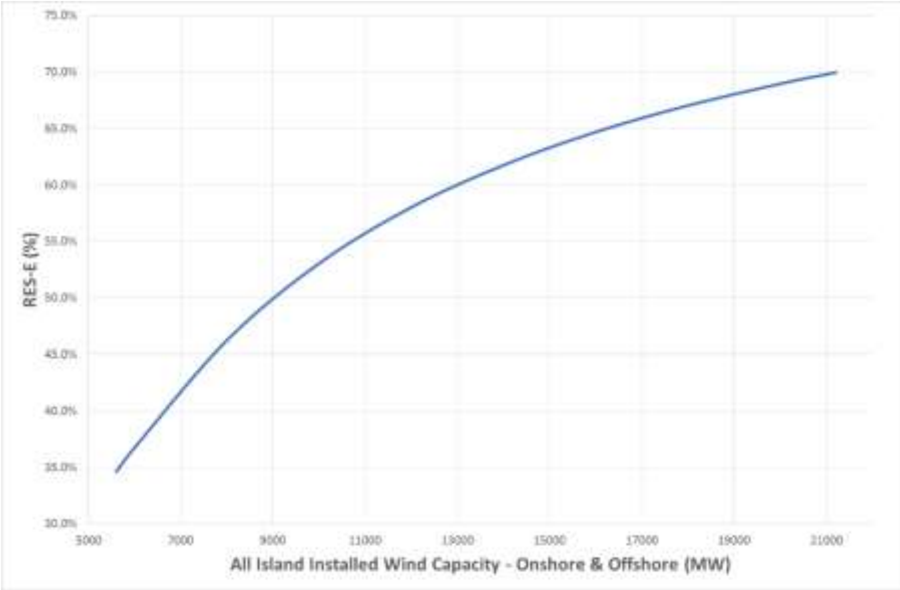


Figure 6 Required installed wind capacity to achieve 70% RES-E without any mitigation measures.

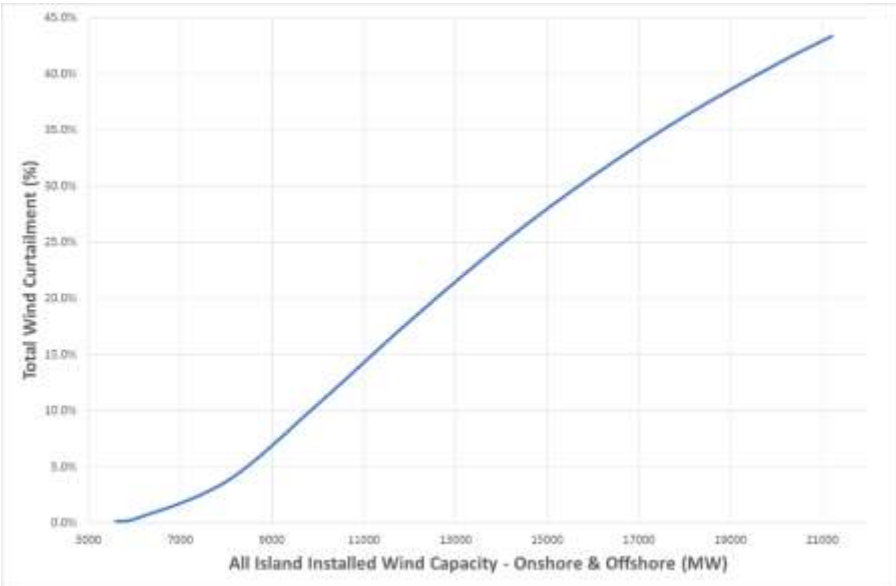
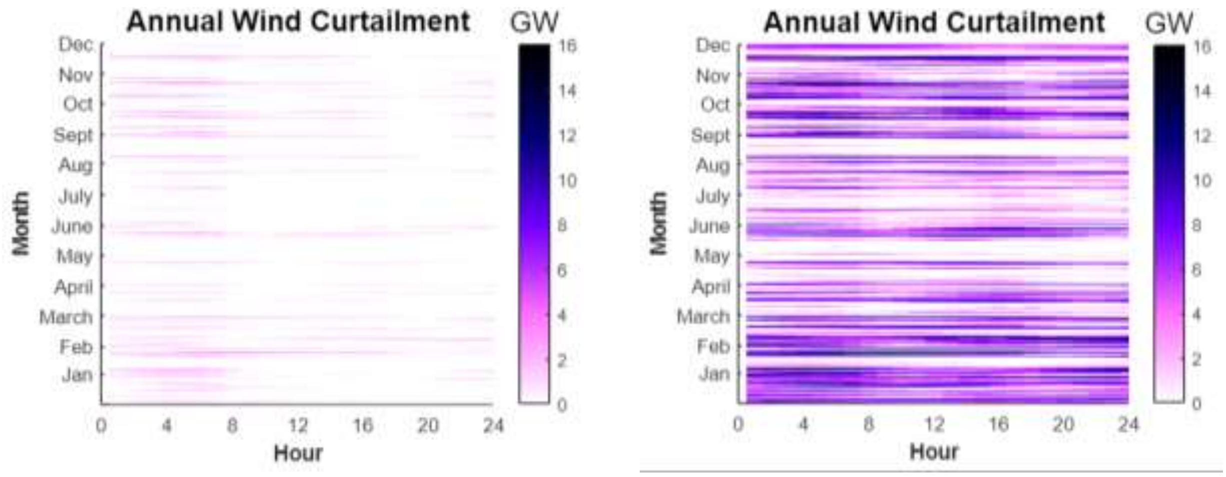


Figure 7 Total Wind Curtailment vs Installed Wind Capacity without any mitigation measures.



(a) (b)

Figure 8 MATLAB analysis results (a) 48% RES-E with 5% curtailment 2030 (b) 70% RES-E with 43% curtailment 2030.

5.2 WP-3a Develop Base Case Scenario for Solar

This work package was identical to work package 3 except solar capacity was added to the system instead of wind capacity. The results of the analysis are summarised in the tables and figures below. Key conclusions / observations:

- Even accounting for the wind capacity already installed on the system in 2020, (which is providing approximately 35% RES-E), it isn't theoretically possible to get to 70% RES-E by adding solar capacity alone. Once the installed capacity reaches a certain level, eventually all additional available energy provided by further capacity is wasted through curtailment.
- The nature of the solar curtailment problem is fundamentally different to the wind curtailment problem. While wind curtailment events at very high penetration levels have very long durations, solar curtailment, for obvious reasons, occurs over much shorter durations. However, the intensity of the curtailment taking place during these shorter events is much higher. This is clearly illustrated in Figure 11.

Table 6 Wind & Solar increase to 2030

Scenario	Solar IC (MW)	RES-E (%)	Total Solar Curtailment (%)	Controllable Solar Curtailment (%)	Events (no.)	Average Duration (hrs)	Maximum Duration (hrs)	Total hrs of curtailment events (hrs)
1	1	34.6%	0.0%	0.0%	26	3.3	7.0	87
2	5000	41.9%	1.3%	1.7%	85	3.3	14.0	280
3	10000	47.2%	12.2%	16.2%	266	4.0	17.0	1074
4	15000	50.0%	25.5%	34.1%	319	5.2	17.0	1670
5	20000	51.7%	35.9%	47.9%	351	5.8	18.0	2046
6	25000	53.0%	43.7%	58.3%	381	6.1	18.0	2325
7	35000	54.6%	54.6%	72.8%	401	6.7	18.0	2703
8	40000	55.2%	58.6%	78.1%	394	7.3	18.0	2868
9	50000	56.1%	64.7%	86.2%	394	7.9	19.0	3097

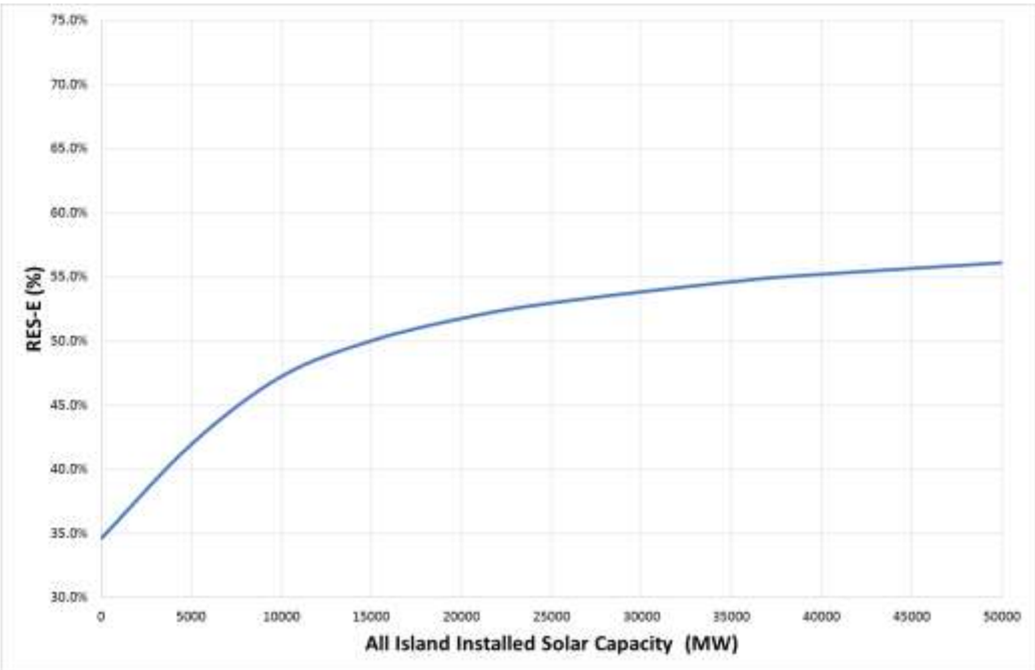


Figure 9 Required installed wind capacity to achieve 55% RES-E without any mitigation measures.

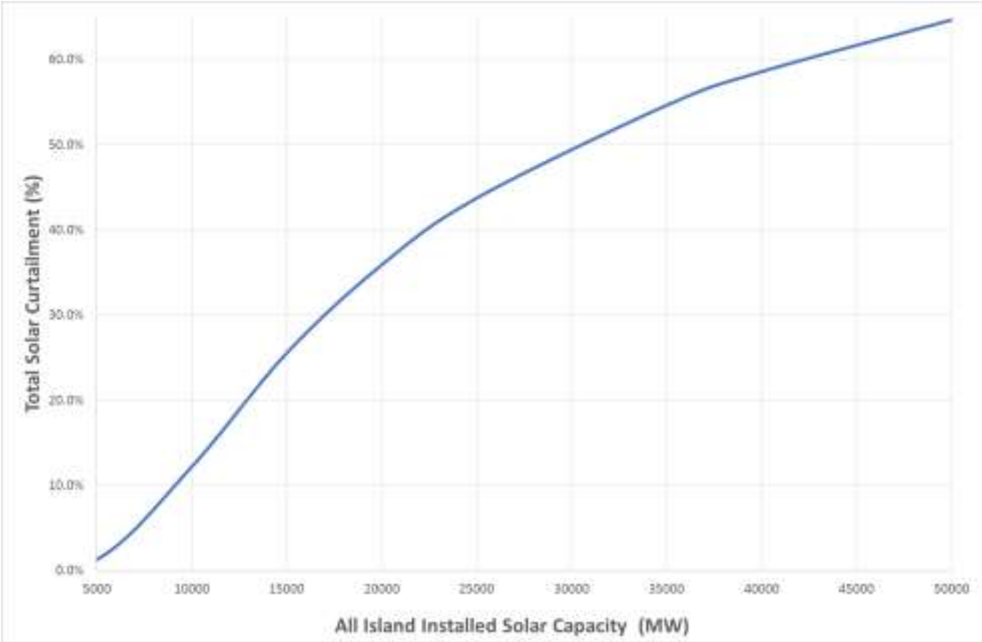


Figure 10 Total solar curtailment vs Installed solar capacity without any mitigation measures.

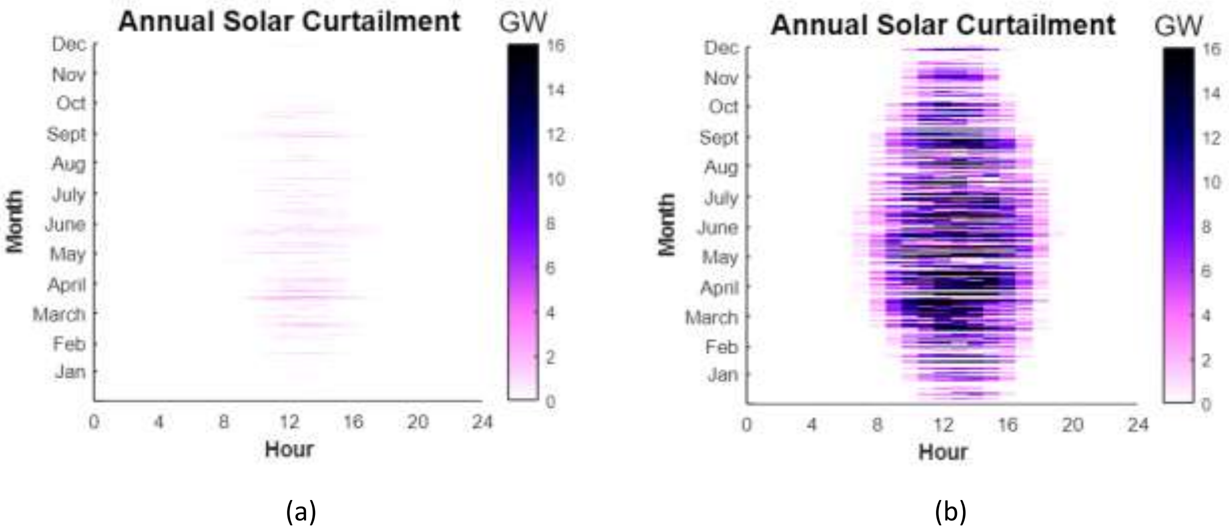


Figure 11 MATLAB analysis results (a) 45% RES-E with 5% curtailment 2030 (b) 55% RES-E with 55% curtailment 2030.

5.3 WP-4 Analyse the Impact of SNSP and Min Gen Levels on Curtailment

In this work package we conducted a detailed multi scenario analysis to look at the theoretical impact of SNSP limits increasing from 75% (the level expected to be achieved in 2020), incrementally up to 100%, and minimum all island conventional generation constraint reductions starting at 1400MW (the approx. level expected to be achieved by 2020), reducing incrementally down to 0MW. It is important to note that every point on every chart represents 70% RES-E, i.e. as we implemented a mitigation measure which has the effect of reducing curtailment, this had the further benefit of reducing the amount of MW's of installed capacity required to reach 70%. Table 7 illustrates the curtailment levels for a range of SNSP and Min Gen limits. Table 8 shows the corresponding required installed wind capacity to reach a 70% RES-E level. The curtailment analysis is presented graphically in Figure 12.

Key conclusions / observations:

- Further increases in the SNSP limit will, on its own, have only a limited impact on curtailment. It is necessary to also address the other operational constraints that result in a minimum level of conventional generation on the system. This should be done by incrementally working to remove the constraints that bind most on curtailment at each step.
- If alternative solutions can ultimately be found for all existing system operational constraints, this alone could solve more than 70% of the entire curtailment problem identified in WP3. This is due to the fact that removing conventional generation from the system, results in space on the system that is energy unlimited. i.e. If 1400MW of storage capacity is added to the system it always has some energy limitation. It becomes full or empty after some hours. However, if 1400MW of minimum conventional generation can be removed from the system, this space is available at all times to be filled by renewables when they are available. It never becomes "full".
- Achieving this will at a minimum require the procurement of system stability services including inertia, fast frequency response / reserves and reactive power compensation from non-fossil fuelled providers, and the systems services market would need to be adapted to facilitate these new providers. The results of the first DS3 volume capped auctions have already illustrated how cost effective these solutions can be when provided under an appropriately designed market framework. High CAPEX and low OPEX technologies require higher revenue certainty to reduce the cost of capital for deployment and there is likely a case to be made for even longer duration contracts for these technologies in the future.
- From a curtailment perspective, the space created for renewables by removing these operational constraints would be relatively "safe". Once the system is sufficiently flexible to be able to operate at very low conventional generation levels, the marginal cost of renewable generation in the market should ensure that it can be dispatched in "real world" conditions.
- EirGrid's DS3 programme has been critical for minimising curtailment of the wind generation required to meet the 2020 RES-E targets. The extension of the DS3 programme is required to address the new challenges of managing 70% RES-E on the Irish system by 2030. This will include workstreams to increase the SNSP limit towards 90-100% and also ensuring there is the system services required for a very high RES-E system. The provision of these system services from non-fossil fuel generation should result in the reduction of levels of conventional generation required on the system at times of high renewables. EirGrid's involvement in the EU funded Sys-Flex study should provide some of the critical system analysis required for the next stages of DS3.

Table 7 Curtailment levels for varying SNSP (%) & Minimum Conventional Generation (MW) limits.

Curtailment Levels %							
		SNSP %					
		75%	80%	85%	90%	95%	100%
MIN GEN (MW)	1400	43.36%	39.65%	39.62%	39.62%	39.51%	39.62%
	1200	41.40%	34.70%	33.63%	33.63%	33.63%	33.63%
	1000	40.84%	32.13%	28.52%	28.50%	28.50%	28.50%
	800	40.82%	31.35%	25.14%	24.04%	24.04%	24.04%
	600	40.80%	31.32%	23.97%	20.42%	20.41%	20.26%
	400	40.78%	31.29%	23.93%	18.26%	17.14%	17.14%
	200	40.75%	31.14%	23.76%	18.01%	14.38%	14.30%
	0	40.62%	31.11%	23.74%	17.99%	13.57%	12.02%

Table 8 Required installed wind capacity (MW) for varying SNSP & Minimum Conventional Generation limits.

Required Wind Capacity (MW)							
		SNSP %					
		75%	80%	85%	90%	95%	100%
MIN GEN (MW)	1400	21,200	19,900	19,900	19,900	19,850	19,900
	1200	20,500	18,400	18,100	18,100	18,100	18,100
	1000	20,300	17,700	16,800	16,800	16,800	16,800
	800	20,300	17,500	16,050	15,800	15,800	15,800
	600	20,300	17,500	15,800	15,100	15,100	15,050
	400	20,300	17,500	15,800	14,700	14,500	14,500
	200	20,300	17,450	15,750	14,650	14,025	14,000
	0	20,250	17,450	15,750	14,650	13,900	13,650

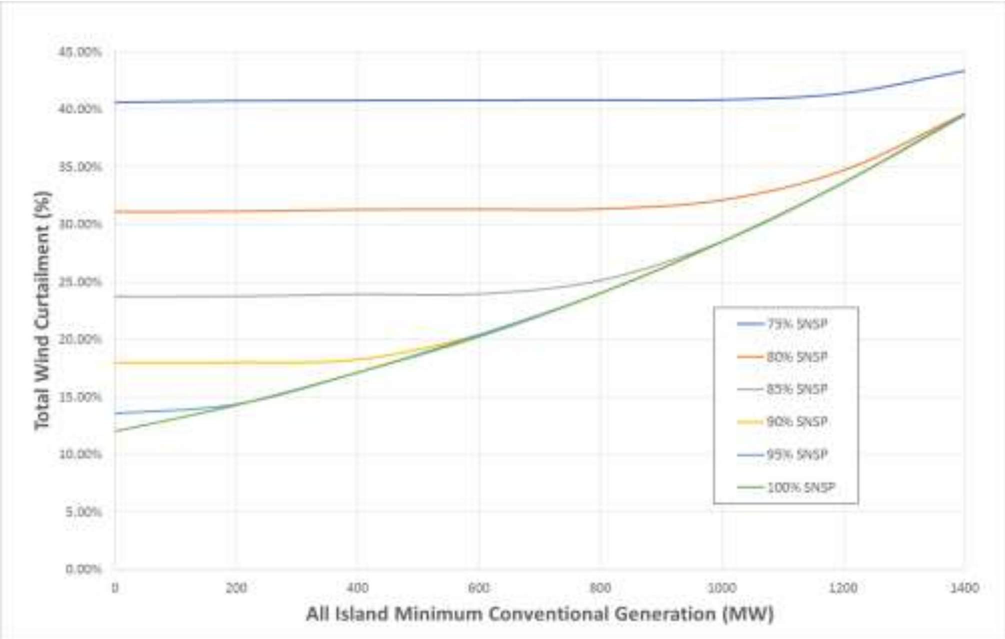


Figure 12 70% RES-E Scenarios - Total Wind Curtailment vs SNSP & Minimum Conventional Generation Limits.

5.4 WP-5 Compare Curtailment Levels for Varying Capacity Factors of Wind Generation

In this work package we assessed the impact of increasing the blended capacity factor of the installed wind fleet. Starting from a level of 30% which is representative of the capacity factor in 2020 and increasing this all the way to 50% which would be representative of the capacity factors that could be achieved offshore or onshore with appropriate incentivisation. A natural upward trend in capacity factors can be expected due simply to the improving turbine technologies and increases in rotor sizes, however absent specific incentivisation, the rotor diameter increases will likely be accompanied by increases in generator Maximum Export Capacities (MEC's) and this would likely dampen the expected capacity factor improvements. It is important to note that this is a system benefit rather than a project benefit. i.e. Any individual project wouldn't be able to reduce it's own curtailment by increasing its capacity factor. As such projects would be unlikely to make a decision to move away from a cost optimal turbine selection ahead of an auction in order to contribute to a broader system benefit that would be shared by all other projects.

As the capacity factor of the fleet is increased, the total installed capacity required to reach 70% RES-E reduces and this results in lower levels of curtailment. The results are summarised in the tables and graphs below.

As noted above, the analysis presented in this report outlines the electricity system benefits associated with optimising the capacity factor of wind and solar projects in the pipeline. At present, there are no incentives in place to ensure renewable energy developers are delivering projects which are optimised on a highest capacity factor basis. With current policy, developers identify suitable technology that returns the lowest LCOE for the project. In the case of a windfarm, the capacity factor can be optimised with higher hub heights that allow access to higher wind speeds, while larger swept areas can increase output across the range of operating wind speeds. When optimising for LCoE these larger rotor diameters are typically accompanied by larger generator sizes which produce more energy but have the effect of reducing the capacity factor that these larger rotors would otherwise deliver. There is a trade-off involved in the slightly higher costs for longer blades and taller towers, but an overall reduction in LCOE can be achieved with the right optimisation. In order to realise potential system benefits from higher capacity factor technology, it is vital that future policy should consider an appropriate scheme for rewarding generators on an individual basis for providing wider system benefits. Under the existing system, a decision to choose a higher capacity factor turbine model would result in some additional cost to the individual but the associated benefit would be shared across the entire fleet. The RESS auctions may be used as a mechanism to incentivise higher capacity factor projects.

The DCCAE recently published the "Terms and Conditions for the First Competition under the Renewable Electricity Support Scheme" document which sets out the terms and conditions that will apply to the first auction to be conducted under the RESS and to the ongoing administration of awards made in the RESS 1 Auction. In the auction process and for the purposes of winner selection, each offer price will be converted into a deemed offer price through the application of an "evaluation correction factor" which is listed by each eligible technology and renewable capacity factor. The "evaluation correction factor" could be a potential lever that assists in the deployment of optimised capacity factor generation.

Key Conclusions / Observations:

- Incentivising a high fleet capacity factor has the potential to have a significant positive impact of the curtailment levels on the system.
- This assumes that the average capacity factor of the entire fleet reaches this level. In reality the legacy of older turbines with lower capacity factors exporting on the system in the period past 2030 would limit the extent to which the fleet could improve over this timeframe. However, if higher capacity factor turbines are incentivised now, then initial modest improvements in the near term would become gradually more and more significant in the longer term as older plant is decommissioned and replaced, and this could become extremely important in a 2030 - 2040 timeframe as renewable ambitions continue to increase.
- Determining the appropriate extent of incentivisation to strike the right balance between the curtailment savings and a "high capacity factor premium / service payment" requires further study and a well-designed market mechanism.
- DCCAE and other key stakeholders as appropriate, should consult on incorporating appropriate incentives into RESS auctions which reward renewable projects that provide a system benefit through optimised capacity factors. This should be designed such that the overall cost of energy to consumers is reduced. i.e. such that the shared benefits exceed any cost of providing the incentive.

Table 9 Compare curtailment levels for varying Wind Capacity Factors.

Scenario	Wind C.F. (%)	Wind IC (MW)	Total Wind Curtailment (%)
1	30.0%	28000	51.4%
2	32.0%	24200	47.3%
3	34.0%	21200	43.4%
4	36.0%	18750	39.5%
5	38.0%	16750	35.9%
6	40.0%	15150	32.7%
7	42.0%	13775	29.5%
8	44.0%	12575	26.3%
9	46.0%	11600	23.6%
10	48.0%	10750	21.0%
11	50.0%	10000	18.5%

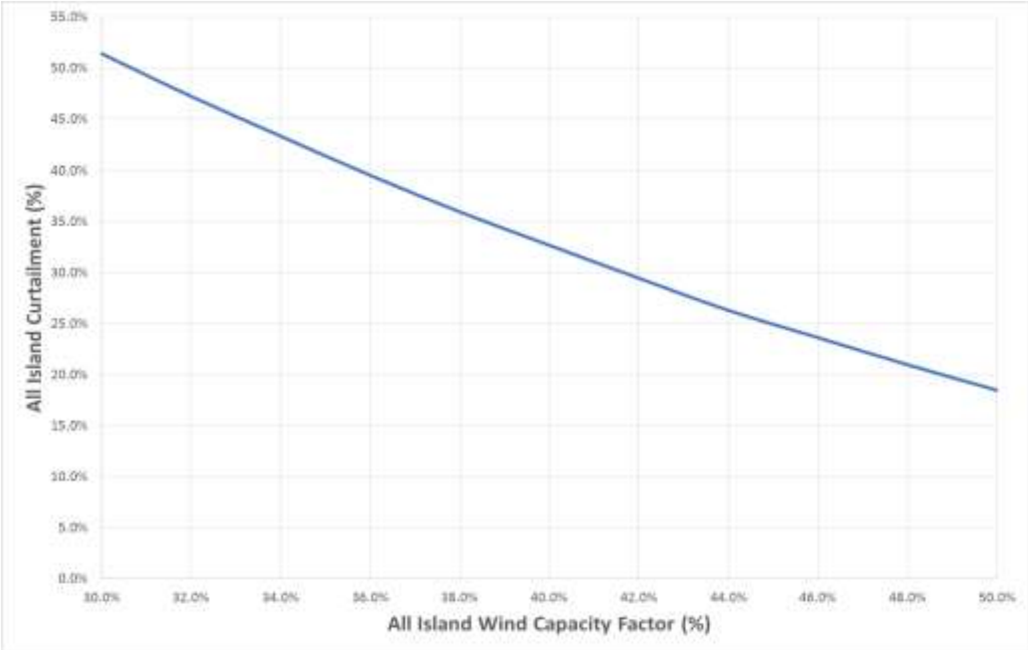


Figure 13 Total Wind Curtailment vs All Island Wind Capacity Factor.

5.5 WP-6 Analyse the Impact of Adding Solar Capacity to the Generation Fleet

Solar and wind generation output have a somewhat inverse correlation. In this work package we analysed the positive impact of this inverse correlation by gradually increasing the share of solar capacity in the mix from 0 to 15,000MW. We start with the installed wind capacity determined in WP3 as being required to reach 70% RES-E. We then start adding solar energy to the mix. As solar energy is added, this allows the installed wind capacity to be reduced while still retaining a 70% RES-E level. Initially we see a reduction in curtailment but as we continue to increase the amount of solar installed on the system, eventually we reach a minimum curtailment level, at which point further increases in installed solar capacity start to result in increases in curtailment. It should be noted that this "sweet spot" is very likely dependent on the interaction with the remaining system assumptions. i.e. If we change the SNSP / min gen limits, wind capacity factors, levels of interconnection etc then the optimal level of solar to minimise curtailment would be expected to change. The detailed results are outlined in the tables and figures below.

Key conclusions / observations include:

- For this specific set of system assumptions, the system curtailment continued to reduce until there was 10GW of installed solar capacity on the system. This is due to the somewhat inverse correlation between the output of wind and solar generation.
- It should be noted that this is the optimised mix from a curtailment minimisation perspective for a specific set of system assumptions. Depending on the relative cost of wind and solar energy, the optimal mix from a consumer cost perspective could be quite different.
- The curtailment improvement noted was material, but much less impactful than that seen in WP4 & 5.

Table 10 Compare curtailment levels for an increasing share of solar in the renewable mix.

Scenario	Wind IC (MW)	Solar IC (MW)	Total Renewable Curtailment (%)	Total Wind Curtailment (%)	Total Solar Curtailment (%)
2	21100	500	43.0%	43.2%	16.3%
3	20700	1000	42.3%	42.7%	18.5%
4	20200	1500	41.4%	41.9%	18.6%
5	19800	2000	40.7%	41.3%	18.9%
6	19500	2500	40.2%	41.0%	19.3%
7	18700	3000	39.4%	40.4%	19.6%
8	18700	3500	38.7%	39.7%	20.0%
9	18400	4000	38.2%	39.3%	20.5%
10	18100	4500	37.7%	38.9%	21.0%
11	17800	5000	37.2%	38.5%	21.6%
12	17500	5500	36.7%	38.1%	22.1%
13	17200	6000	36.2%	37.6%	22.7%
14	17000	6500	36.0%	37.4%	23.5%
15	16800	7000	35.8%	37.2%	24.3%
16	16600	7500	35.6%	37.0%	25.2%
17	16400	8000	35.5%	36.8%	26.1%
18	16200	8500	35.3%	36.6%	26.9%
19	16000	9000	35.1%	36.3%	27.8%
20	15900	9500	35.2%	36.4%	28.8%
21	15700	10000	35.1%	36.1%	29.6%
22	15400	11000	35.1%	35.9%	31.4%
23	15200	12000	35.4%	35.9%	33.3%
24	15000	13000	35.7%	35.9%	35.0%
25	14800	14000	36.0%	35.9%	36.7%
26	14600	15000	36.4%	35.8%	38.3%

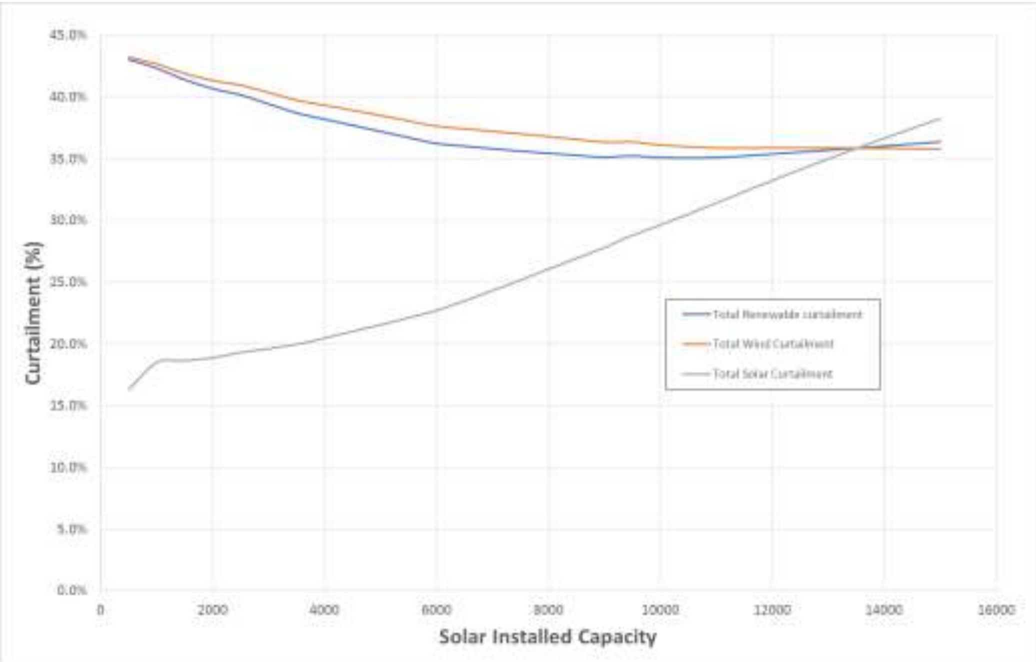


Figure 14 All Island Installed Solar Capacity vs Curtailment (wind adjusted to 70% RES-E for all points).

5.6 WP-7 Analyse the Impact of Interconnectors and Storage on Curtailment "High Wind"

In this work package we conducted a multi scenario analysis examining the impact of gradually increasing the "idealised" interconnector capacity and "idealised" storage capacity with varying energy limitations. In this context idealised interconnectors means that the model was always able to export up to the full available capacity to mitigate curtailment. In the context of storage, it means that the model tried every other means of mitigating curtailment before charging a storage technology (due to its energy limitation), and then once a curtailment event was over it sought to discharge the storage technology as quickly as possible to maximise its availability for the next event. i.e. The results below should be considered as the theoretical maximum curtailment benefit that can be provided by each technology.

The analysis was run first with the 70% RES-E system that emerged from WP3, described as the "high wind" system. In order to determine whether storage technologies would interact more favourably with solar we also ran a set of scenarios starting with the optimal wind / solar mix that emerged from WP6, described as the "high solar" system. The results of this set of scenarios is shown in WP7a below.

Table 11 Impact of interconnectors on curtailment.

Scenario 1 - Interconnectors				
Scenario	Idealised Interconnector Capacity (MW)	Additional Idealised IC Capacity (MW)	Wind IC (MW)	Wind Curtailment (%)
1.1	380	0	21,200	43.4%
1.2	880	500	17,450	31.1%
1.3	1380	1000	15,500	22.5%
1.4	1880	1500	14,350	16.3%
1.5	2380	2000	13,600	11.7%
1.6	2880	2500	13,075	8.2%
1.7	3380	3000	12,700	5.5%

Table 12 Impact of battery & pumped hydro storage on curtailment.

Scenario 2 - 3hr storage 80% return trip				Scenario 4 - 15hr storage 80% return trip			
Scenario	Additional Storage Capacity (MW)	Wind IC (MW)	Wind Curtailment (%)	Scenario	Additional Storage Capacity (MW)	Wind IC (MW)	Wind Curtailment (%)
2.1	0	21,200	43.4%	4.1	0	21,200	43.4%
2.2	500	20,900	42.5%	4.2	500	20,300	40.6%
2.3	1000	20,700	41.8%	4.3	1000	19,600	38.3%
2.4	1500	20,500	41.2%	4.4	1500	19,000	36.1%
2.5	2000	20,300	40.6%	4.5	2000	18,500	34.3%
2.6	2500	20,100	40.0%	4.6	2500	18,100	32.7%
2.7	3000	20,000	39.6%	4.7	3000	17,800	31.4%
Scenario 3 - 6hr storage 80% return trip				Scenario 5 - 30hr storage 80% return trip			
3.1	0	21,200	43.4%	5.1	0	21,200	43.4%
3.2	500	20,700	41.9%	5.2	500	19,900	39.3%
3.3	1000	20,300	40.6%	5.3	1000	18,900	35.8%
3.4	1500	20,000	39.6%	5.4	1500	18,100	32.7%
3.5	2000	19,700	38.6%	5.5	2000	17,500	30.1%
3.6	2500	19,400	37.6%	5.6	2500	17,000	27.9%
3.7	3000	19,150	36.8%	5.7	3000	16,600	26.0%

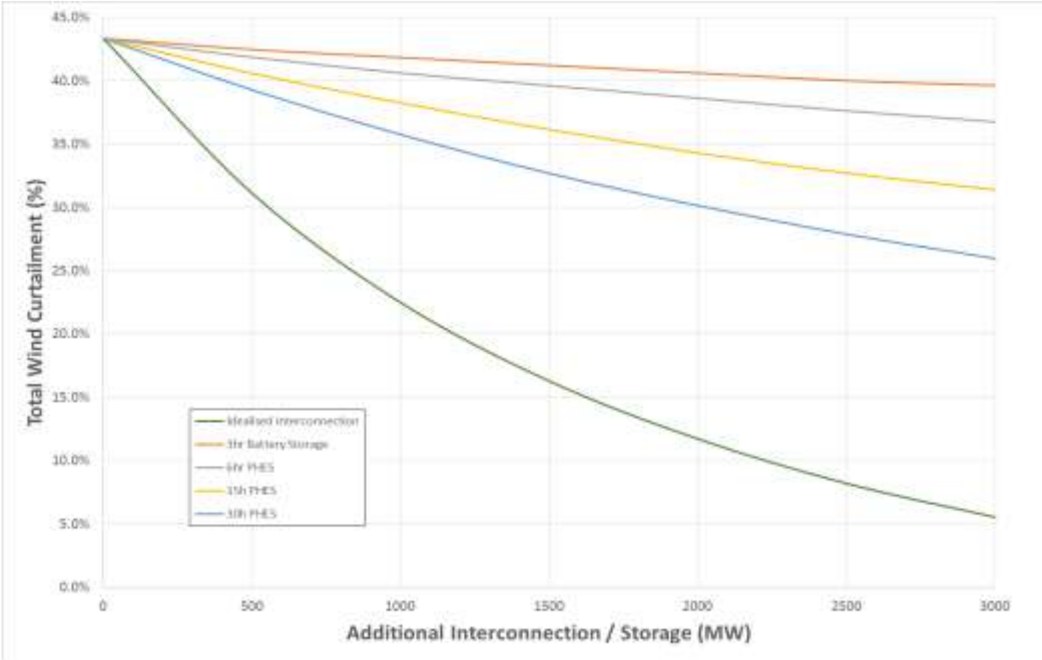


Figure 15 All Island wind curtailment (High Wind) Vs Additional idealised interconnection and storage.

Key conclusions / observations for “High Wind” system.

- Energy limited storage technologies have limited direct curtailment mitigation benefits.
- Interconnector capacity has the potential to provide very significant curtailment mitigation benefits, however the actual curtailment mitigation performance of interconnectors will depend on the generation mix and costs of the systems to which they are connected, and likely on the future evolution of EU wholesale market design. We would suggest this as an area for further study. For this reason, we would classify the modelled curtailment benefits from additional interconnector capacity in this study as being less “safe” than the benefits predicted in WP4,5 & WP6.
- While battery storage has very little direct impact on curtailment, these technologies do have other potential system benefits that should be further explored, including providing fast frequency response, reserves, ramping and reactive power services, as an alternative to fossil fuelled peaking capacity and as a potential solution to local grid constraints (particularly demand constraints).

5.7 WP-7a Analyse the Impact of Interconnectors and Storage on Curtailment - High solar

As noted above, in this work package we started with the "optimal" wind / solar mix identified in WP6 to determine whether the addition of storage capacity would interact better with a high solar capacity system. The results are summarised in tables and figures below.

Key conclusions / observations:

- The results indicate that a high solar system responds better to the addition of limited duration storage technologies though this improvement is not hugely material. The generation profile of solar in Ireland particularly during the winter months is very concentrated into a relatively small number of hours and on a very high solar system this can create a profile with very high peaks in these hours. i.e. notwithstanding the fact that the solar profile is more regular, there is still a lot of energy at these peak hours that needs to be time shifted and this still presents a challenge when attempting to achieve this utilising energy limited storage technologies.

Table 13 Impact of interconnectors on curtailment –high solar.

Scenario 1 – Interconnectors				
Scenario	Idealised Interconnector Capacity (MW)	Additional Idealised IC Capacity MW	Wind IC (MW)	Total Renewable Curtailment (%)
1.1	380	0	15,700	35.1%
1.2	880	500	12,850	23.4%
1.3	1380	1000	11,500	16.2%
1.4	1880	1500	10,700	11.3%
1.5	2380	2000	10,200	7.9%
1.6	2880	2500	9,850	5.5%
1.7	3380	3000	9,650	4.0%

Table 14 Impact of battery & pumped hydro storage on curtailment –high solar.

Scenario 2 - 3hr storage 80% return trip				Scenario 4 - 15hr storage 80% return trip			
Scenario	Additional Storage Capacity (MW)	Wind IC (MW)	Total Renewable Curtailment (%)	Scenario	Additional Storage Capacity (MW)	Wind IC (MW)	Total Renewable Curtailment (%)
2.1	0	15,700	35.1%	4.1	0	15,700	35.1%
2.2	500	15,300	33.6%	4.2	500	14,700	31.1%
2.3	1000	15,000	32.3%	4.3	1000	14,000	27.9%
2.4	1500	14,700	31.1%	4.4	1500	13,400	25.0%
2.5	2000	14,500	30.2%	4.5	2000	12,950	22.7%
2.6	2500	14,300	29.3%	4.6	2500	12,600	20.7%
2.7	3000	14,150	28.6%	4.7	3000	12,300	18.9%
Scenario 3 - 6hr storage 80% return trip				Scenario 5 - 30hr storage 80% return trip			
3.1	0	15,700	35.1%	5.1	0	15,700	35.1%
3.2	500	15,100	32.7%	5.2	500	14,450	30.0%
3.3	1000	14,600	30.6%	5.3	1000	13,550	25.7%
3.4	1500	14,200	28.8%	5.4	1500	12,825	22.0%
3.5	2000	13,850	27.2%	5.5	2000	12,300	18.9%
3.6	2500	13,575	25.9%	5.6	2500	11,925	16.5%
3.7	3000	13,350	24.7%	5.7	3000	11,575	14.2%

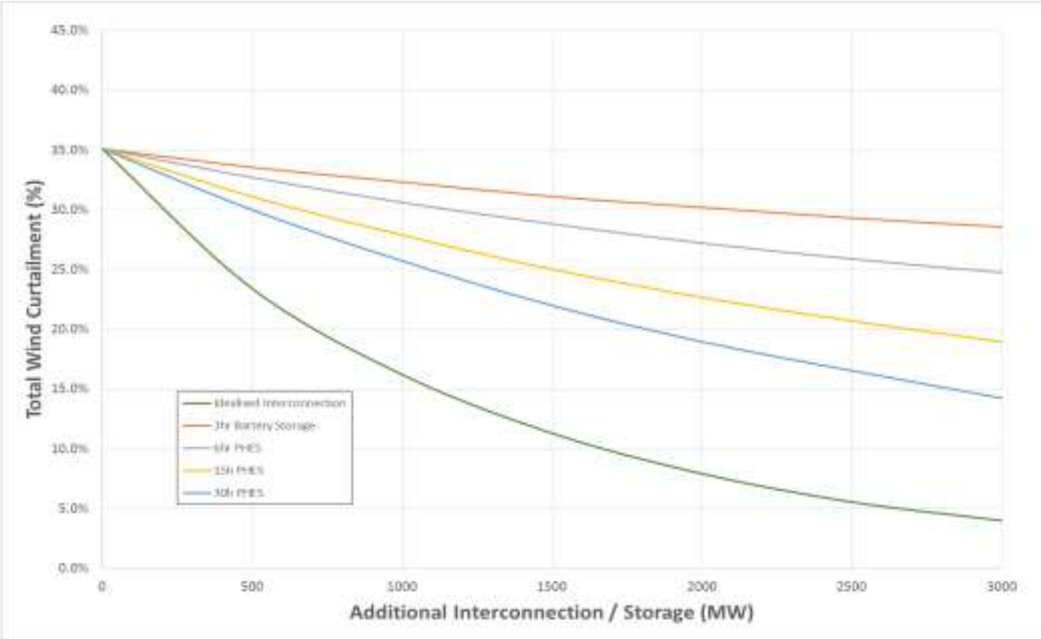


Figure 16 All Island renewable curtailment (High Solar) Vs additional idealised interconnection and storage.

5.8 WP-8 Impact of Demand Flexibility on Curtailment Levels

In this work package we analysed the direct curtailment benefits of incorporating varying levels of demand side flexibility.

In the first set of scenarios we looked at the impact of increasing levels of flexibility from the EV fleet. A range of percentages from 0% to 100% of the daily EV demand were assigned as being flexible within each day. Where possible, this flexible portion of the demand was time shifted to the hours in the day where curtailment was occurring. Where it wasn't possible to mitigate curtailment (primarily when there were all day long curtailment events) the model sought to reduce the required ramp rates for the remaining conventional plant. The results of this analysis are illustrated in Figure 17 and show that the flexibility of EV demand has very little direct impact on renewables curtailment at this high level of renewables penetration.

In the second set of scenarios we added flexibility from the heat pumps on the system. This is a binary on / off setting in the model. We modelled all heat pump systems as having 500l water cylinders and that the water temperature in these cylinders must be maintained between 25°C and 55°C. An hourly heat demand profile [25] is applied to this system and where no curtailment is occurring, the model allows the temperature in the cylinder to drop to its minimum allowable level as heat is taken from the cylinder. By always allowing energy to be taken from the system at times of low renewables generation, this creates the theoretical maximum headroom to absorb energy at times of surplus renewables. During curtailment events, the model then sends any surplus energy to heat the water in the cylinder up to its maximum allowable temperature, all the while meeting the heat demand profile. Heat dissipation losses were also incorporated in each hour, though the overall system losses due to this effect were relatively modest. These assumptions would be considered to be extremely optimistic from a curtailment mitigation perspective, compared to the capabilities / operation of heat pump systems currently being installed. Figure 17 shows the added benefits of incorporating this heat flexibility. Again, the benefits were very modest. We would however note that there could be a more significant benefit if district heating was deployed with much larger hot water reservoirs / tanks as the available energy storage volume could potentially be much greater.

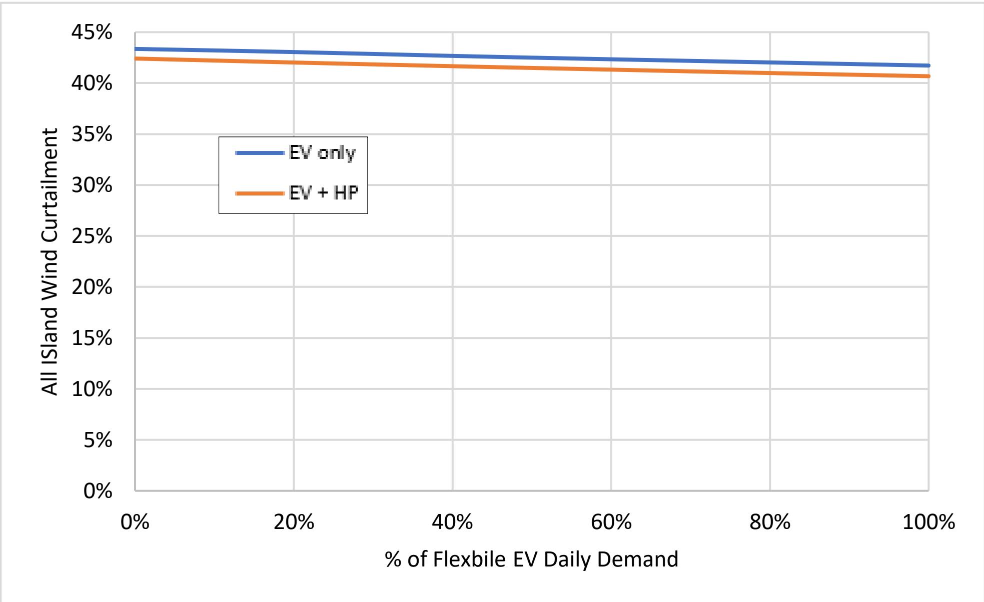


Figure 17 Curtailment vs % of flexible EV demand with and without utilisation of Heat storage.

In the third set of scenarios we examined the benefit of background demand flexibility. This incorporated all demand excluding electric vehicles, heat pumps and datacentres. A range of percentages from 0% to 20% of the total background electricity demand were assigned as being flexible within each day. The flexible MWh's were then time shifted using the same algorithm that was applied to the EV demand in the first set of scenarios. This resulted in a greater impact than in the first two sets of scenarios primarily due to the significant increase in daily flexible MWh's, though still a modest impact when compared to some of the earlier work packages. The results of this set of scenarios is shown in Figure 18 below.

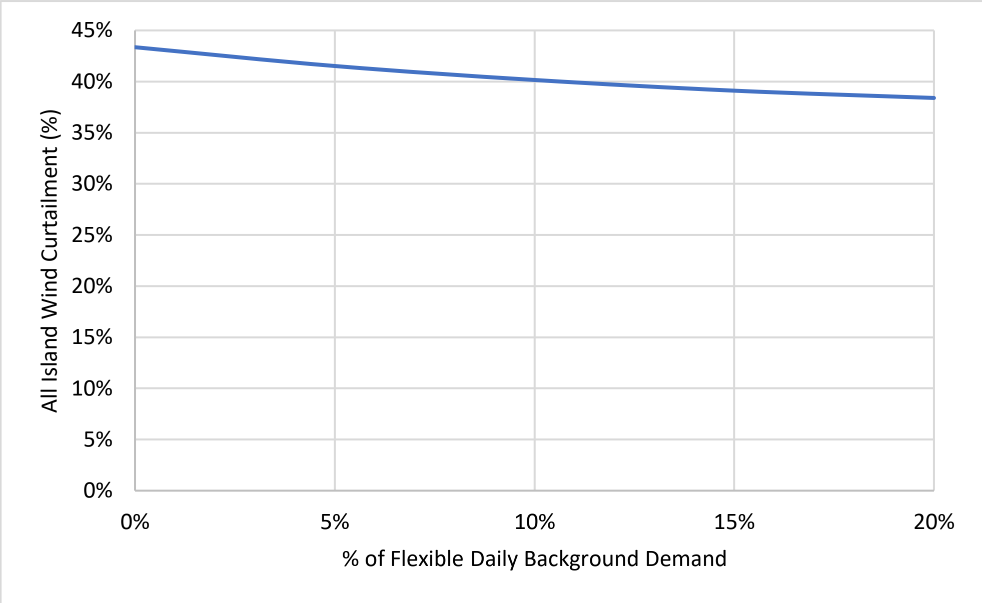


Figure 18 Curtailment vs % of flexible daily background demand.

In the fourth scenario, we combined optimistic but plausible levels of flexibility from each of the first three sets. The curtailment mitigation achieved is not insignificant but would still be relatively modest when compared to some of the earlier work packages. Results are as indicated in Figure 19 below.

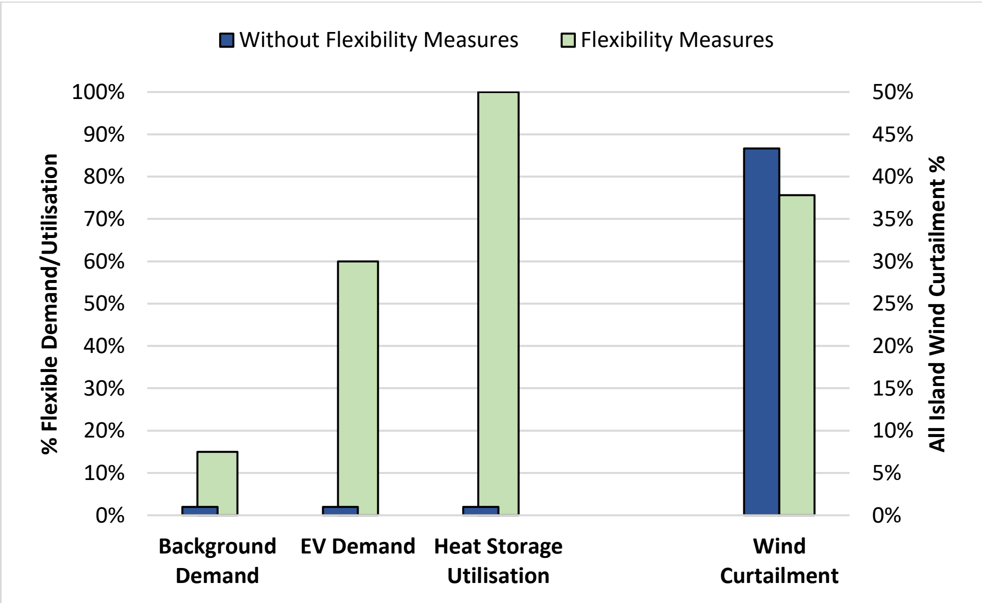


Figure 19 Curtailment vs Combined demand flexibility measures.

Table 15 Impact of EVs on curtailment.

Scenario 1 - EV flexibility without using heat storage			
Scenario	% of EV demand fully flexible each day (%)	Wind Curtailment (%)	MWh Wind Curtailment (MWh)
1	0%	43.36%	27,345,089
1.2	20%	43.05%	27,023,877
1.3	40%	42.67%	26,608,659
1.4	60%	42.34%	26,251,100
1.5	80%	42.03%	25,921,964
1.6	100%	41.72%	25,595,758

Table 16 Combined impact of EVs and heat pumps on curtailment.

Scenario 2 - Utilise Heat storage in combination with % of EV flexibility					
Scenario	% of EV demand fully flexible each day (%)	Wind Curtailment (%)	MWh Wind Curtailment (MWh)	MWh reduction in curtailment due to HP (MWh)	Heat dissipation losses (MWh)
2.1	0%	42.41%	26,371,601	973,488	74,767
2.2	20%	42.02%	25,954,782	1,069,094	74,327
2.3	40%	41.66%	25,569,853	1,038,807	73,827
2.4	60%	41.32%	25,214,744	1,036,356	73,524
2.5	80%	40.99%	24,864,412	1,057,552	73,191
2.6	100%	40.68%	24,542,538	1,053,220	72,986

Table 17 Impact of increased background demand flexibility on curtailment.

Scenario 3 - Flexibility of background demand		
Scenario	% of background demand fully flexible each day (%)	Wind Curtailment (%)
1	0%	43.36%
1.1	5%	41.52%
1.2	10%	40.15%
1.3	15%	39.11%
1.4	20%	38.40%

Table 18 Combined impact of demand flexibility measures on curtailment.

Scenario 4 - 60% EV + 15% background + HP flexible				
Scenario	% of background demand flexible (MW)	% of EV Demand Flexible	Heat storage Utilised	Wind Curtailment (%)
1	0	0%	FALSE	43.4%
4.2	15%	60%	TRUE	37.8%

Table 19 Heat pump and water cylinder assumptions.

Heat Pump Assumptions		
COP	3	
Heat Pump Electrical Demand Per Annum	4.301	MWh/yr
Water Cylinder Assumptions		
U-Value of Cylinder	0.60	W/m^{2}K
Cylinder Capacity	500	L
Cylinder Height	1.907	m
Cylinder Radius	0.355	m
Cylinder Material – Thickness	0.0012	m
Polyurethane Insulation – Thickness	0.08	m
Minimum Temperature of Water in Cylinder	25	°C
Maximum Temperature of Water in Cylinder	55	°C
Ambient Temperature of Cylinder Location	22	°C
Material Constants		
Specific Heat Capacity of Water	4186	J/kg/°C
Thermal Conductivity of Stainless-Steel Duplex ldx 2100	20	W/m K
Thermal Conductivity of Polyurethane Foam	0.048	W/m K

Key Observations / Results:

- Demand side management (DSM) has very limited direct curtailment mitigation benefits on systems with this level of renewable generation. In WP9 below, we see the direct benefits increase somewhat if applied after other more effective mitigation measures such as improved operational constraints and increased interconnection but applied in isolation they would be completely insufficient to support a 70% RES-E system.
- However, similar to batteries, DSM does have the potential to provide some of the system services solutions necessary to support the removal of operational constraints and as already noted, this can be a very effective curtailment mitigation measure. In addition, DSM also has the potential to contribute to capacity adequacy, at least partially offsetting the need for fossil fuel peaking generation and could also potentially mitigate demand side network constraints. Measuring these benefits is outside the scope of this study but would be an area for further work.

5.9 WP-9 Feasible 2030 Scenario - Proposal for High RES-E at Low Curtailment in 2030

In this work package we started out with a blended 2030 wind capacity factor of 34%, all other system assumptions were as assumed for 2020 and applied the assumed 2030 demand levels. We then sought to implement feasible levels of each of the mitigation measures in turn and determine how much space this created for increased RES-E. Installed wind was adjusted until curtailment reached a maximum of 5% for every scenario.

The results are summarised in the tables below and show that RES-E could exceed 83% while keeping curtailment below 5%, due to the combined effect of plausible levels of all of these mitigation measures. There are however several important caveats to these results:

- Within this analysis, new interconnectors were assumed to export an average of 90% of their available capacity at times of surplus renewables. As interconnector flows are currently based on wholesale prices in neighbouring jurisdictions this outcome is not guaranteed. In 2018 during periods of curtailment of wind generation in Ireland the EWIC interconnector was on average exporting only 36% of its available capacity, based on analysis undertaken by Mullan Grid Consulting. Under current market timelines and rules on price formation, circumstances are arising where conventional generation in one jurisdiction can be operating above its minimum technically feasible level and this system can be exporting power across an interconnector into a system that is curtailing zero marginal cost renewable power. This would appear to be a somewhat perverse market outcome. We would suggest this as an area for further research to determine whether these outcomes are either cost or carbon optimal on a first principles basis. There may be potential to improve future market designs to facilitate greater renewable integration by seeking to facilitate greater exports from jurisdictions with surplus renewable power into jurisdictions where there is the technical scope to reduce marginal cost fossil fuel generation.
- Achieving a blended fleet capacity factor of 38% by 2030 is likely to be quite challenging given that most of the 2020 fleet is likely to still be operational in 2030. However, with some incentivisation, a blended capacity factor in excess of this level for of all new wind generation post 2020 should easily be achievable, both on and offshore. As the older fleet is decommissioned and re-powered post 2030, the full system benefits of higher capacity factors will likely be realised.

- Removing operational constraints such that the proposed SNSP levels of 90% and min gen levels of 700MW, will require complex engineering analysis and solutions, combined with regulatory support for increased system services funding. Provided these levels can be reached the space that they create on the system is safe from a curtailment perspective, but the challenge of achieving this shouldn't be underestimated.
- The benefits of DSM for curtailment and RES-E are greater when they are implemented after all other measures. The earlier mitigation measures have the effect of making curtailment more of a day/night problem and in these circumstances, DSM can start to have a more meaningful impact.

Given the uncertainties around some of these assumptions we also conducted a series of sensitivities on the proposed 83% RES-E system. These are summarised in Table 25.

Table 20 Relieved operational constraints 2030.

Scenario 1 - Relieve existing operational constraints						
Scenario	Min Gen (MW)	SNSP (%)	All Island Wind Installed Capacity (MW)	Wind Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
1	1400	75%	8420	4.98%	4.93%	47.9%
1.2	1100	80%	9010	4.98%	4.94%	51.0%
1.3	800	85%	9600	4.99%	4.95%	54.1%
1.4	700	90%	9850	4.99%	4.95%	55.4%

Table 21 Increased interconnector capacity 2030.

Scenarios 2 - Add Celtic & Greenwire Interconnectors, assume all Interconnectors are 90% effective						
Scenario	Installed Interconnector capacity (MW)	Modelled Interconnector Capacity (MW)	All Island Installed Wind Capacity (MW)	Wind Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
2.1	580	522	10090	4.97%	4.93%	56.7%
2.2	1280	1152	11190	4.97%	4.94%	62.4%
2.3	1780	1602	11980	4.99%	4.96%	66.6%
2.4	2020	1818	12350	4.98%	4.95%	68.5%

Table 22 Increased wind capacity factor 2030.

Scenarios 3 - Increasing Blended Wind Capacity Factors					
Scenario	Blended Wind Capacity Factor (%)	All Island Wind Installed Capacity (MW)	Wind Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
3.1	35.0%	12230	4.99%	4.96%	69.8%
3.2	36.0%	12110	4.99%	4.96%	71.1%
3.3	37.0%	12000	4.99%	4.96%	72.3%
3.4	38.0%	11870	4.96%	4.93%	73.5%

Table 23 Increasing the share of solar capacity in the renewable mix 2030.

Scenarios 4 - Adding solar capacity to the mix						
Scenario	Solar Installed capacity (MW)	All Island Wind Installed Capacity (MW)	Total Wind Curtailment (%)	Total Solar Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
4.1	1000	11790	4.97%	1.52%	4.90%	74.1%
4.2	2000	11660	4.98%	1.93%	4.85%	74.9%
4.3	3000	11510	4.96%	2.36%	4.80%	75.6%
4.4	4000	11360	4.97%	2.86%	4.79%	76.3%
4.5	5000	11190	4.95%	3.39%	4.78%	76.8%
4.6	6000	11010	4.95%	4.10%	4.84%	77.3%
4.7	7000	10830	4.99%	5.01%	5.00%	77.6%

Table 24 Implementing background demand EV flexibility measures & deploying additional wind capacity 2030.

Scenarios 5 - Adding demand side flexibility and additional wind								
Scenario	Enable Flexible Heat Demand TRUE/FALSE	Background Demand Flexible each day (%)	EV Demand Flexible each day (%)	All Island Installed Wind Capacity (MW)	Total Wind Curtailment (%)	Total Solar Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
5.1	FALSE	5%	20%	11260	5.00%	4.32%	4.90%	80.2%
5.2	FALSE	10%	40%	11495	4.99%	3.99%	4.85%	81.7%
5.3	FALSE	15%	60%	11650	4.99%	3.76%	4.82%	82.6%
6.1	TRUE	15%	60%	11760	4.98%	3.76%	4.82%	83.2%

Table 25 Sensitivity analysis 2030.

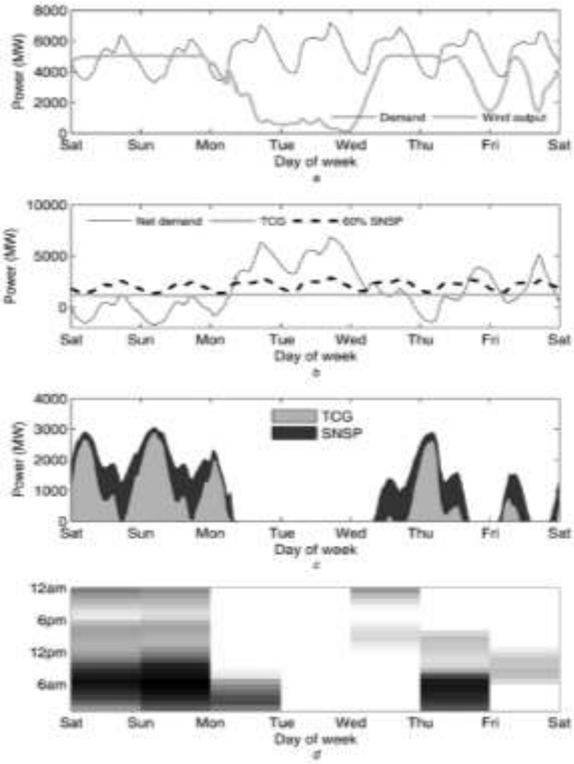
Scenarios 6 - Sensitivity Analysis on Scenario 6.1									
		Absolute Values				Deltas			
Scenario	6.1 unchanged in every scenario below except where noted in each description line	Total Wind Curtailment (%)	Total Solar Curtailment (%)	Renewable Curtailment (%)	RES-E (%)	Total Wind Curtailment (%)	Total Solar Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
6.1 A(i)	Operational Constraint Sensitivity - 800MW Min Gen, 85% SNSP	6.72%	4.97%	6.48%	81.8%	1.74%	1.19%	1.66%	-1.41%
6.1 A(ii)	Operational Constraint Sensitivity - 1000MW Min Gen, 80% SNSP	9.22%	6.66%	8.87%	79.8%	4.24%	2.89%	4.06%	-3.43%
6.1 B(i)	Interconnector "Effectiveness" reduced from 90% to 80%	5.90%	4.35%	5.69%	82.5%	0.92%	0.57%	0.87%	-0.74%
6.1 B(ii)	Interconnector "Effectiveness" reduced from 90% to 60%	8.06%	5.71%	7.74%	80.7%	3.08%	1.93%	2.92%	-2.48%
6.1 B(iii)	Interconnector "Effectiveness" reduced from 90% to 40%	10.67%	7.37%	10.22%	78.6%	5.69%	3.60%	5.41%	-4.58%
6.1 C (i)	Blended Wind Capacity Factor reduced from 38% to 36%	4.36%	3.25%	4.20%	80.0%	-0.62%	-0.52%	-0.61%	-3.19%
6.1 C (ii)	Blended Wind Capacity Factor reduced from 38% to 34%	3.81%	2.82%	3.66%	76.8%	-1.18%	-0.95%	-1.16%	-6.42%
6.1 D (i)	Reduce Installed solar capacity to 3500MW	3.66%	2.00%	3.54%	78.8%	-1.33%	-1.77%	-1.28%	-4.41%
6.1 E (i)	Reduce background demand flexibility from 15% to 5%, EV flexibility from 60% to 30% and remove heat flexibility	6.25%	5.00%	6.08%	82.2%	1.27%	1.23%	1.26%	-1.03%

5.10 WP-10 Animation of 2030 Scenario

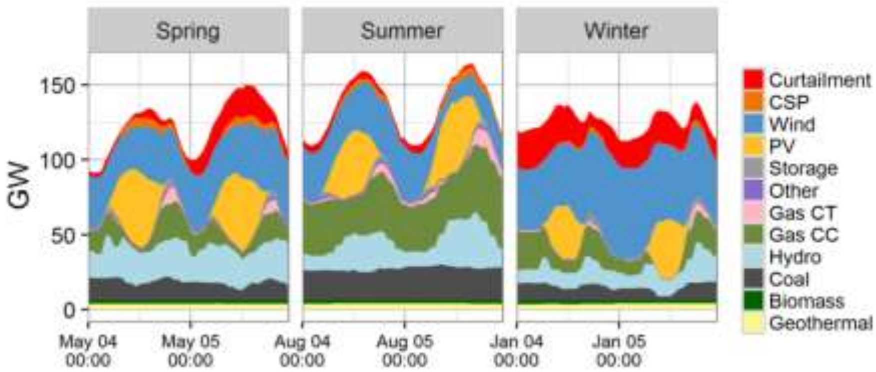
The aim was to provide the results of the curtailment analysis and mitigation measures using animation where possible. These animations would help to understand the impact of the mitigation measures on curtailment levels.

A number of reports from literature were reviewed to understand the standard and most relevant data that could be presented and the way this data has been presented by others.

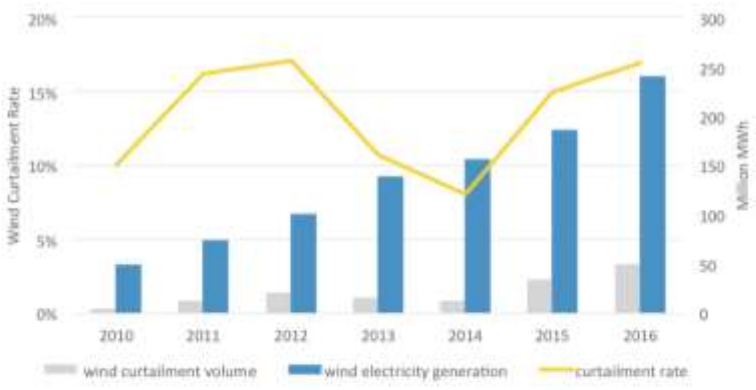
Some models presented Generation, Demand, SNSP, Total Curtailment, Net Curtailment, etc with respect to time across various intervals; hours, days, weeks, months, years (using different specifications including interconnectors, SNSP levels, etc) as shown in Figure 20.



(a)



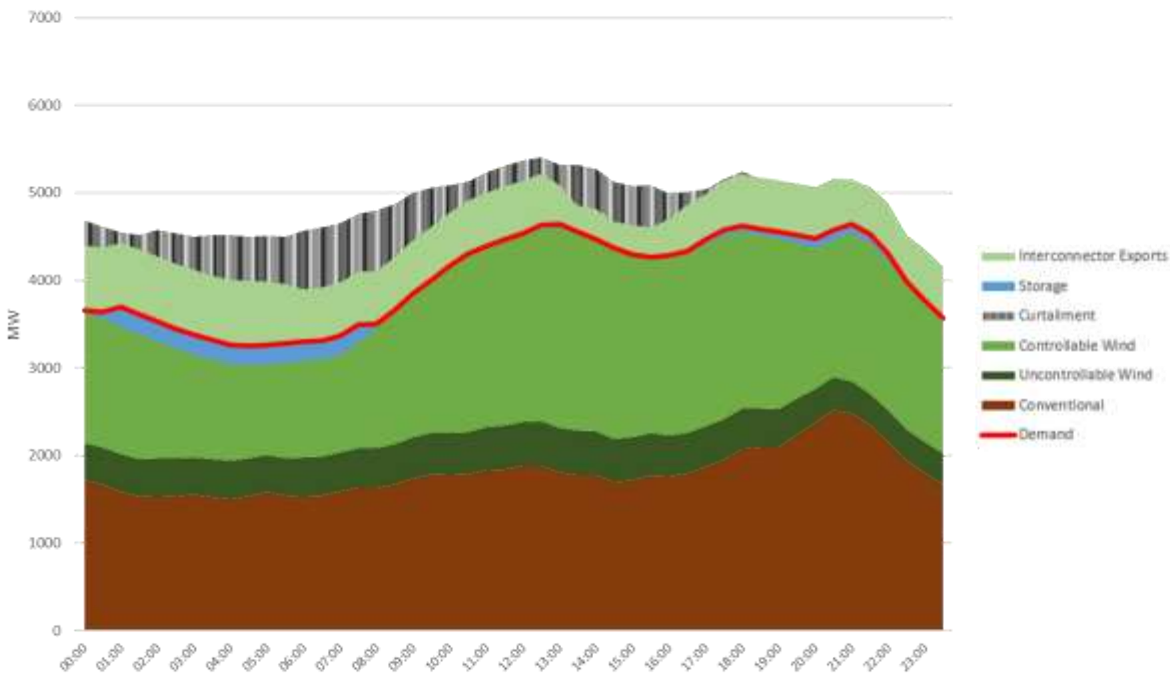
(b)



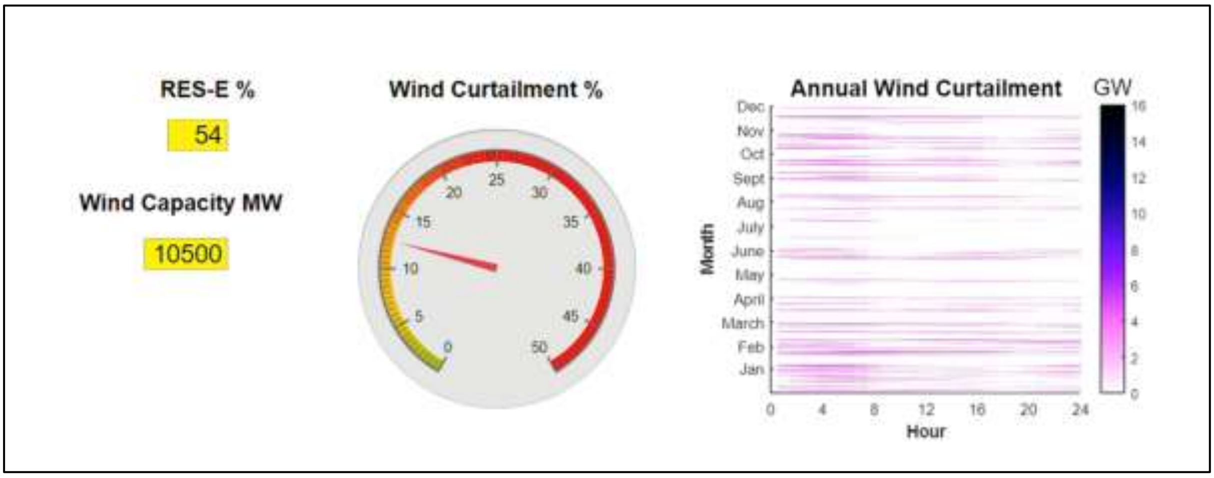
(c)

Figure 20 Various models presenting curtailment results (a) Ireland [26] (b) US [27] (c) China [28].

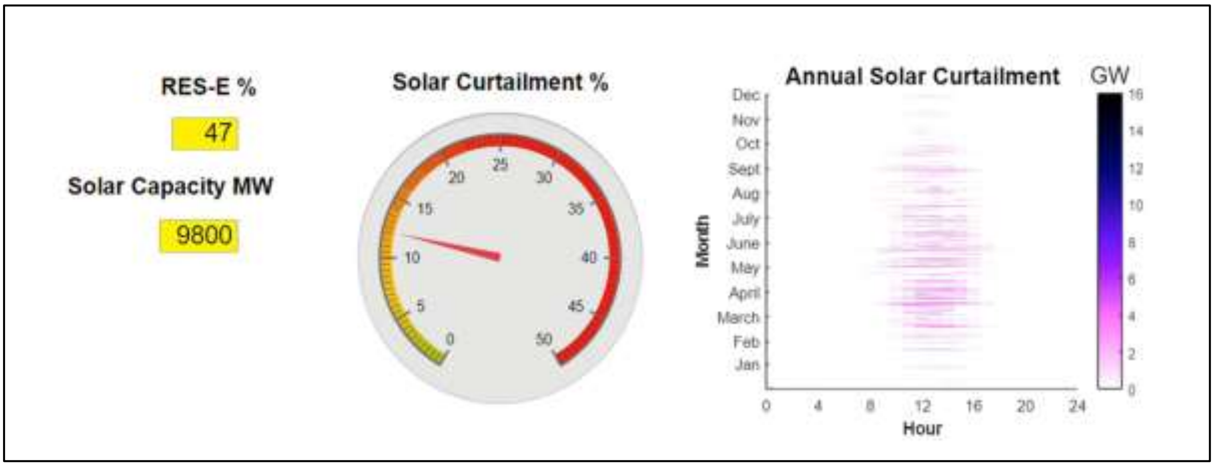
The animations were completed in MATLAB and presented in PowerPoint. Some examples are shown in Figure 21 Example animations from MATLAB analysis. The presentation of the curtailment results including the animations can be found at the following links: Presentation PDF, Presentation Video.



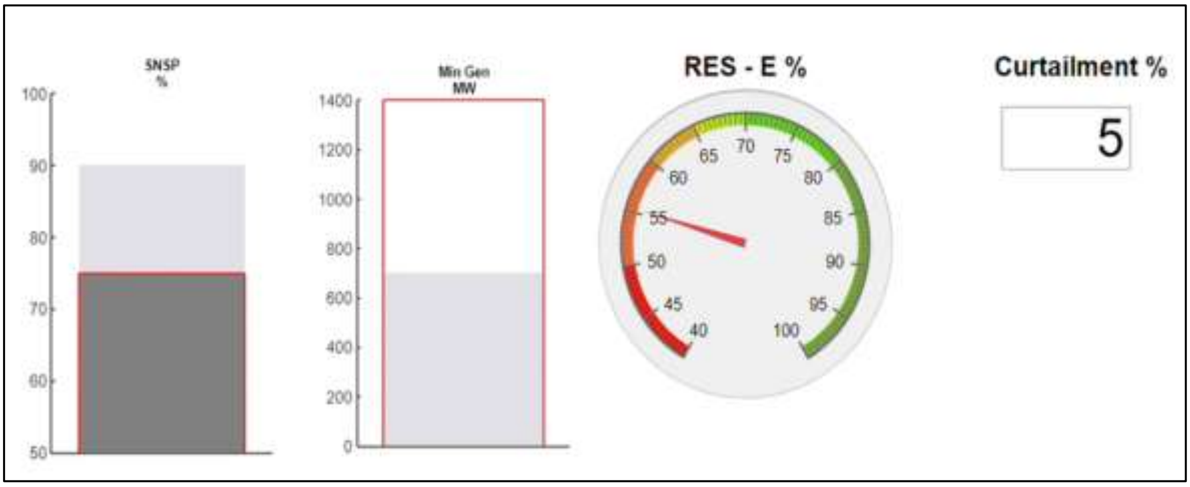
(a) Example illustrating wind curtailment.



(b) Example of wind curtailment animation (without mitigation measures).



(c) Example of solar curtailment animation (without mitigation measures).



(d) Example of an animation of SNSP and Min Gen curtailment mitigation measures.

Figure 21 Example animations from MATLAB analysis.

5.11 WP11 2040 Scenarios Analysis

In WP11 a number of potential pathways to reaching 100% RES-E by 2040 are explored.

Table 26 2040 input assumptions (all Island).

Renewables Installed capacity		All Island (MW)	C.F. avail %	
Total Wind		12370 – 13890	38 - 44%	
Total Solar		7000	10.0%	
Uncontrollable Wind		751		
Uncontrollable Solar		1750		
Balancing Technologies Installed Capacity	MW (charging / Exporting)	MW (Discharging / Importing)	Eff (%)	MWh
Idealised Interconnectors	1818	1818	100%	1.00E+26
Existing Pumped Hydro	219	219	80%	1314
New Pumped Hydro	0	0	80%	0
Batteries	0	0	80%	0
Conventional Generation	0	9000	100%	1.00E+26
Hydrogen PtG	0	0	60%	1.00E+26
Idealised Interconnectors	1818	1818	100%	1.00E+26
System Parameters				
SNSP Limit		90 - 100%		
Conventional Minimum Generation		700 – 0	MW	
Demand				
% increase in 2015 Baseline (RoI)		10.92%		
% increase in 2015 Baseline (NI)		10.36%		
Additional datacentres above 2015		1591.25	MW	
Number of electric vehicles added to baseline		1,158,092	No.	
Number of heat pumps added to baseline		749,011	No.	
Average Cylinder Size in heat pump system		500	litres	
Maximum water temperature		55	deg C	
Minimum water temperature		25	deg C	
Ambient house temperature		22	deg C	
% of flexible background demand		15%		
% of flexible data centre demand		0%		
% of flexible EV demand		60%		
Utilise storage capacity of heat		TRUE		

Pathway 1: Further operational constraint improvements, higher capacity factors and higher curtailment

In the first set of scenarios we further implement some of the measures used in WP9. We began with the system identified as the end point of WP9 and then gradually removed all operational constraints, i.e. we assume that by 2040 the system could operate with 100% non-synchronous generation. We then assumed further improvements in capacity factors as older generators go offline and turbine technologies continue to improve. This left us a little short of 100% RES-E if we limited curtailment to 5%. To bridge the gap to 100% RES-E we allowed curtailment to increase to 7.7%.

It should be noted that this is made up of approximately 87.3% RES-E used locally and 12.7% being exported. This 12.7% that is exported during times of surplus renewables then either needs to be imported or provided by some small amount of conventional generation locally, at times of lower wind. We specifically didn't increase interconnector capacities in this scenario as there would be some concerns that as the UK and continental Europe also move to very high RES-E systems, the effectiveness of the interconnectors may start to reduce.

Table 27 2040 Scenario Results - Scenario 1, 2, 3.

Scenario 1 - Relieve existing operational constraints						
Scenario	Min Gen (MW)	SNSP (%)	All Island Wind Installed Capacity (MW)	Wind Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
1.1	700	90%	12370	5.0%	4.9%	82.2%
1.2	500	90%	12460	5.0%	4.9%	82.7%
1.3	250	95%	13150	5.0%	4.8%	86.6%
1.4	0	100%	13625	5.0%	4.8%	89.2%

Scenarios 2 - Increasing Blended Wind Capacity Factors					
Scenario	Blended Wind Capacity Factor (%)	All Island Wind Installed Capacity (MW)	Wind Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
2.1	40.0%	13350	5.0%	4.9%	91.6%
2.2	42.0%	13075	5.0%	4.9%	93.8%
2.3	44.0%	12825	5.0%	4.9%	96.0%

Scenarios 3 - Accept higher curtailment				
Scenario	All Island Wind Installed Capacity (MW)	Wind Curtailment (%)	Renewable Curtailment (%)	RES-E (%)
3.1	13250	6.1%	6.0%	97.7%
3.2	13500	6.8%	6.6%	98.6%
3.3	13750	7.5%	7.3%	99.5%
3.4	13890	7.9%	7.7%	100.0%

Table 27 shows the results of the further operational constraint improvements, higher capacity factors and higher curtailment until we get to 100% RES-E.

Pathway 2: A 100% RES-E system - Increasing role for Power-to-Gas

As noted above there would be some concerns around potential reductions in the effectiveness of interconnectors over the next 10-20 years. Also, the technical challenges of achieving a 100% non-synchronous system are relatively high and this would be a further risk to this 100% RES-E pathway. As such we then considered the potential role of seasonal storage technologies. The technology most often put forward as a solution to the problem of seasonal storage is electrolysis of water to Hydrogen or Power-to-Gas. In the paragraphs below we outline a number of potential roles for power-to-gas in the 2030 to 2040 timeframe. In order for these options to be available we would suggest that Ireland should be looking for opportunities to support development of pilot projects of scale in the 2020 to 2030 timeframe.

Table 28 2040 input assumptions (all Island).

Renewables Installed capacity		All Island (MW)	C.F. avail %	
Total Wind		13890 - 17620	38 - 44%	
Total Solar		7000	10.0%	
Uncontrollable Wind		751		
Uncontrollable Solar		1750		
Balancing Technologies Installed Capacity	MW (charging / Exporting)	MW (Discharging / Importing)	Eff (%)	MWh
Idealised Interconnectors	1818	1818	100%	1.00E+26
Existing Pumped Hydro	219	219	80%	1314
New Pumped Hydro	0	0	80%	0
Batteries	0	0	80%	0
Conventional Generation	0	9000	100%	1.00E+26
Hydrogen PtG	0	0	60%	1.00E+26
Idealised Interconnectors	1818	1818	100%	1.00E+26
System Parameters				
SNSP Limit		90 - 100%		
Conventional Minimum Generation		700 - 0	MW	
Demand				
% increase in 2015 Baseline (RoI)		10.92%		
% increase in 2015 Baseline (NI)		10.36%		
Additional datacentres above 2015		1591.25	MW	
Number of electric vehicles added to baseline		1,158,092	No.	
Number of heat pumps added to baseline		749,011	No.	
Average Cylinder Size in heat pump system		500	litres	
Maximum water temperature		55	deg C	
Minimum water temperature		25	deg C	
Ambient house temperature		22	deg C	
% of flexible background demand		15%		
% of flexible data centre demand		0%		
% of flexible EV demand		60%		
Utilise storage capacity of heat		TRUE		

Table 29 Power-to-Gas notes hydrogen.

Load Factor on the electrolyser for this run	0 - 33.96%
Assumed efficiency of electrolyser	58%
Equivalent RES-E going to RES-H & RES-T	0 – 13.88%
Total Equivalent RES-E	99.9 – 101.78%

The RES-E Calculation used in the model was updated with the deducted renewable MWh going to electrolysers, this is dealt with separately on the summary pages. Interconnector effectiveness is also assumed to be reduced in 2040 due to higher RES-E penetrations in other jurisdictions as previously discussed.

Power-to-Gas Role 1: Reduce curtailment

In the first piece of analysis we start with the 100% scenario identified above as a base case, this left a renewable curtailment rate of 7.7%, and added electrolyser capacity to take curtailment back to below 5% (i.e. SNSP @ 100%, min gen at 0MW, IC capacity at 90%, Wind CF at 44%). As more electrolyser capacity is added to the system there is more energy that would otherwise be curtailed / wasted that can be dispatched to the electrolysers to generate hydrogen / green gas. The amount of electricity dispatched to the electrolysers is then multiplied by the assumed electrolyser efficiency to determine the energy content of the gas produced by the system. This energy after efficiency losses is effectively electrical energy that has been moved to the heat (via the gas grid [22][23][29]) or the transport sector as fuel for fuel cell vehicles [30][31]. In order to make the figures comparable we convert this heat / transport energy into an equivalent RES-E number as noted in Table 30 below (i.e. the heat / transport energy is divided by the total demand for electricity). The curtailment benefits are also noted in Table 30. It is worth noting that across these results, the capacity factor of the electrolyser is relatively low and as such the commercial case to do this would likely be extremely challenging. We would also note that the capacity factor of the electrolysers is reducing for each incremental reduction in curtailment, i.e. the lower the curtailment is on the system; the more commercially challenging it is to deploy electrolysers to mitigate it further.

Table 30 2040 Scenario Results with hydrogen – curtailment mitigation.

Scenario	Installed wind (MW)	Wind Curtailment (%)	Installed Electrolyser (MW)	Electrolyser CF (%)	RES-E (%)	Equivalent RES-E to H&T (%)	Equivalent RES-E (%)
1.1	13890	7.9%	0	0.0%	99.9%	0.0%	99.9%
1.2	13890	6.8%	250	28.5%	99.9%	0.6%	100.5%
1.3	13890	5.8%	500	27.1%	99.9%	1.2%	101.1%
1.4	13890	4.9%	750	25.8%	99.9%	1.8%	101.7%
1.5	13890	4.1%	1000	24.6%	99.9%	2.2%	102.1%

Power-to-Gas Role 2: Offset higher operational constraints

In the next set of results we change the operational constraints such that only 90% SNSP and 700MW min gen is possible and then try to get to 100% RES-E by adding electrolysers and more wind while keeping curtailment below 5%. As we add electrolyser capacity we can add additional wind capacity because the electrolysers are able to manage the associated potential curtailment. The electrolysers take this energy and convert it to hydrogen / green gas that can then be diverted to the heat and transport sector and if you add enough electrolyser and wind capacity you generate enough hydrogen / green gas to get to the equivalent of 100% RES-E. This is an obvious or expected result, however there are two more interesting observations to be made in the results below.

Because the electrolysers are able to manage the curtailment, a higher installed capacity of wind is able to build out on the system. This higher installed capacity is able to meet electrical demand more of the time during times of lower / median winds (i.e. times when curtailment wouldn't be occurring) and as such in addition to the obvious direct benefit of the hydrogen / green gas being added to the system, the higher installed capacity also provides additional direct RES-E benefits. It is shown in Table 31, that with 2GW of electrolysers installed this was able to generate 5.7% RES-E equivalent of hydrogen / green gas, but enabled a further 8.1% of direct RES-E production from the larger wind fleet, i.e. the indirect benefit of the electrolysers was significantly greater than the direct benefit that one would tend to focus on. This would seem to be another case of a broader system benefit to the deployment of this technology for which there is, within the existing electricity market framework minimal commercial reward.

The second interesting observation is that as more electrolysers and wind are added the electrolyser capacity factors actually start to go up. One might expect that as we add electrolysers and wind together to keep curtailment at 5% that the effect on electrolyser capacity factors would be neutral i.e. one would cancel the other out, however in reality, as more capacity is added, the hourly profile of energy being sent to the electrolysers changes, resulting in the improved capacity factors. This presents a challenging "chicken & egg" problem when attempting real world deployment.

Table 31 2040 Scenario Results with hydrogen – offsetting higher operational constraints.

Scenario	Installed wind (MW)	Wind Curtailment (%)	Installed Electrolyser (MW)	Electrolyser CF (%)	RES-E (%)	Equivalent RES-E to H&T (%)	Equivalent RES-E (%)
2.1	11630	5.0%	0	0.0%	88.2%	0.0%	88.2%
2.2	13000	5.0%	1000	27.2%	92.9%	2.5%	95.3%
2.3	14390	5.0%	2000	31.4%	96.3%	5.7%	102.0%

Power-to-Gas Role 3: Offset higher operational constraints & lower interconnector effectiveness levels

In this set of scenarios we take the operational constraint assumptions from the previous set of results and then reduce the effectiveness of interconnectors from 90% to 50% during curtailment events, i.e. the installed Interconnectors can only export 50% of their capacity on average during curtailment events. We then try to get to 100% RES-E by adding more electrolysers and more wind, keeping curtailment below 5%. The results are noted in Table 32. The same general trends as the previous analysis are observed, but more electrolyser capacity is obviously required to compensate for the reduced interconnector effectiveness.

Table 32 2040 Scenario Results with hydrogen – offsetting higher operational constraints and lower interconnector effectiveness.

Scenario	Installed wind (MW)	Wind Curtailment (%)	Installed Electrolyser (MW)	Electrolyser CF (%)	RES-E (%)	Equivalent RES-E to H&T (%)	Equivalent RES-E (%)
3.1	10320	5.0%	0	0.0%	79.8%	0.0%	79.8%
3.2	11760	5.0%	1000	28.1%	84.7%	2.6%	87.2%
3.3	13175	5.0%	2000	32.7%	88.1%	5.9%	94.0%
3.4	14575	5.0%	3000	36.0%	90.5%	9.8%	100.3%

Power-to-Gas Role 4: Offset higher operational constraints, lower interconnector effectiveness levels, and lower wind capacity factors

In this set of scenarios we make use of the operational constraint and interconnector assumptions from the previous set of results and then reduce the capacity factors of wind to 38% during curtailment events. We then try to get to 100% RES-E by adding more electrolysers and more wind, keeping curtailment below 5%. The results are noted in Table 33. Again, the same general trends as the previous analysis are observed.

Table 33 2040 Scenario Results with hydrogen – offsetting higher operational constraints, lower interconnector effectiveness and lower wind capacity factors.

Scenario	Installed wind (MW)	Wind Curtailment (%)	Installed Electrolyser (MW)	Electrolyser CF (%)	RES-E (%)	Equivalent RES-E to H&T (%)	Equivalent RES-E (%)
4.1	11000	5.0%	0	0.0%	74.6%	0.0%	74.6%
4.2	11740	5.0%	500	21.6%	77.0%	1.0%	78.0%
4.3	12500	5.0%	1000	23.8%	79.2%	2.2%	81.4%
4.4	13240	5.0%	1500	25.8%	81.1%	3.5%	84.6%
4.5	13970	5.0%	2000	27.5%	82.6%	5.0%	87.6%
4.6	14700	5.0%	2500	29.1%	84.0%	6.6%	90.6%
4.7	15430	5.0%	3000	30.5%	85.1%	8.3%	93.5%
4.8	16150	5.0%	3500	31.7%	86.2%	10.1%	96.2%
4.9	16900	5.0%	4000	33.0%	87.1%	12.0%	99.1%
4.10	17620	5.0%	4500	34.0%	87.9%	13.9%	101.8%

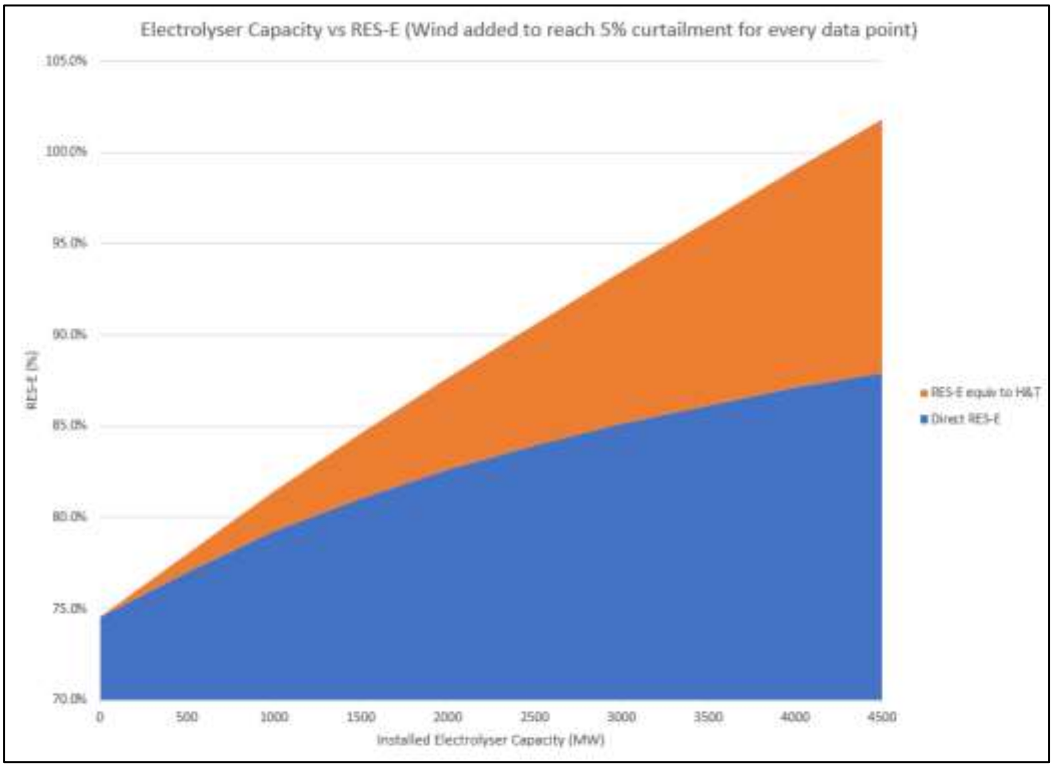


Figure 22 Electrolyser capacity vs RES-E (wind added to reach 5% curtailment for every data point).

Direct and Indirect benefits of additional electrolyser capacities.

Key Conclusions / Observations

- Any study of the electricity system over a timeframe out to 2040, necessarily needs to grapple with considerable uncertainties. The first pathway examined, in simple terms, shows that more of the same measures as were suggested in WP8 & WP9 for 2030 could theoretically get us to a 100% RES-E level in 2040. However, over this timeframe as all EU countries move to decarbonise their power systems, there is a risk that interconnectors in particular may not perform as effectively as they should as modelled in this study initially. In such circumstances, technologies that have the ability to absorb/store significant energy volumes are likely to play an important role. In this respect hydrogen is perhaps one of the most interesting and suitable technologies to examine. This WP shows how power-to-gas technologies could be used to get Ireland to a 100% RES-E equivalent by 2040 without any other system improvements post 2030.

- The results indicate that the first electrolysers installed on the grid are likely to have relatively low capacity factors which makes their initial deployment challenging. These electrolysers would not play a major role in assisting with curtailment, but be commercially viable using alternative business models (such as supply of hydrogen to transport from dedicated wind resources, topped up by curtailed electricity). However, as electrolysers are added at scale, the addition of these enables more wind capacity, we observed a positive feedback such that the capacity factor of all of the electrolysers increased as the power-to-gas and wind sectors grow.
- The electrolysers when operating are able to capture surplus renewable electricity and divert this to the heat and transport sectors (via hydrogen / green gas) and this direct benefit was expected. However, by enabling this additional wind capacity at low curtailment, it can directly meet electricity needs over a greater number of hours in the year. This indirect benefit is very significant. The challenging question here is where does the system or the market value this benefit of power-to-gas and hydrogen. It is not known if there are currently any market mechanisms that would enable a monetary value of this system benefit to be captured by these technology providers, however a number of studies are commencing in Ireland [30]. It will be critically important that regulated markets adapt to keep pace with technological change and changing national renewable policy objectives and ensure that where technologies provide significant system benefits that the providers of these technologies have a means of being rewarded for these benefits.
- This study has not considered the commercial aspects of power-to-gas. Key studies have shown that continued improvements in cost and efficiency will see a large scale up and roll out of this technology. This is already happening in UK, Australia and Netherlands with 100MW scale electrolysers, in planning and to be deployed [32][33][34].
- Power-to-gas systems go beyond producing a basic commodity of hydrogen gas (or energy carrier). In particular, as noted earlier, grid-balancing technologies are required to maintain grid stability with increased numbers of distributed and intermittent renewable sources. Electrolysers, specifically PEM electrolyser technology, can absorb over 100% of its rated energy capacity within seconds, producing renewable hydrogen, and can then be shut down as fast. This makes the technology suitable for demand side management applications and additional revenue. In addition, in market scenarios when electricity price is very low it might make economic sense to import electricity from the grid to produce hydrogen.

6 Conclusions

Conclusion 1

The nature of the curtailment problem at levels of renewables required to meet a 70% RES-E target are fundamentally different from today's curtailment problem. At today's levels of renewable penetration curtailment is mostly a night-time problem. The results of this analysis indicate that when trying to reach a 70% RES-E level on the Irish system, curtailment becomes an all day and in fact multi-day problem. At 70% RES-E, the average duration of discrete curtailment events was 29.4hours, the maximum event duration was 206 hrs and in total there were 5,404hrs in the year during which curtailment was taking place, equivalent to 61% of the entire year.

Conclusion 2

It is theoretically possible to get to 70% RES-E without implementing any additional curtailment mitigation measures, however it requires a massive increase in installed wind capacity and almost half of the available energy is wasted through curtailment. Without new mitigation measurements curtailment levels could reach 45%.

Conclusion 3

It is not theoretically possible to get to 70% RES-E by adding solar capacity alone. Once the installed capacity reaches a certain level, eventually all additional available energy provided by further capacity is wasted through curtailment. The nature of the solar curtailment problem is different to the wind curtailment problem. While wind curtailment events at very high penetration levels have very long durations, solar curtailment, for obvious intraday reasons, occurs over much shorter durations. However, the intensity of the curtailment taking place during these shorter events is much higher.

Conclusion 4

Further increases in the SNSP limit will on its own have only a limited impact on curtailment. It is necessary to also address the other operational constraints that result in a minimum level of conventional generation on the system. If solutions can ultimately be found to remove all existing system operational constraints, including increasing SNSP to 100%, this could solve more than 70% of the entire curtailment problem. This is due to the fact that removing conventional generation from the system, results in space on the system that is energy unlimited. From a curtailment perspective, the space created for renewables by removing these operational constraints would be relatively "safe".

EirGrid's DS3 programme has been critical for minimising curtailment of the wind generation required to meet the 2020 RES-E targets. The extension of the DS3 programme is required to address the new challenges of managing 70% RES-E on the Irish system by 2030. This will include workstreams to increase the SNSP limit towards 90-100% and also ensuring there is the system services required for a very high RES-E system. The provision of these system services from non-fossil fuel generation should result in the reduction of levels of conventional generation required on the system at times of high renewables. EirGrid's involvement in the EU funded Sys-Flex study should provide some of the critical system analysis required for the next stages of DS3.

Conclusion 5

Interconnector capacity has the potential to provide very significant curtailment mitigation benefits, however the actual curtailment mitigation performance of interconnectors will depend on the generation mix and costs of the systems to which they are connected, and likely on the future evolution of EU wholesale market design. We would strongly suggest this as an area for further study. For this reason, we would classify the modelled curtailment benefits from additional interconnector capacity in this study as being less “safe” than the benefits predicted from increasing SNSP and reducing minimum conventional generation levels.

Conclusion 6

A high fleet capacity factor has the potential to have a significant positive impact of the curtailment levels on the system. This assumes that the average capacity factor of the entire fleet reaches this level; in reality the legacy of older turbines with lower capacity factors exporting on the system in the period past 2030 would limit the extent to which the fleet could improve over this timeframe. However, if higher capacity factor turbines are incentivised now, then initial modest improvements in the near term would become gradually more and more significant in the longer term as older plant is decommissioned and replaced, and this could become extremely important in a 2030 - 2040 timeframe as renewable ambitions continue to increase. On this basis we would strongly recommend that DCCAE and other key stakeholders as appropriate, should consult on incorporating appropriate incentives into RESS auctions which reward renewable projects that provide a system benefit through optimised capacity factors. This should be designed such that the overall cost of energy to consumers is reduced. i.e. such that the shared benefits exceed any cost of providing the incentive.

Conclusion 7

Including solar generation in the renewable mix can help reduce overall curtailment levels. This is due to the somewhat inverse correlation between the output of wind and solar generation. For a specific set of system assumptions, the system curtailment continued to reduce until there was 10GW of installed solar capacity on the system. Depending on the relative cost of wind and solar energy, the optimal mix from a consumer cost perspective could be quite different. The curtailment improvement noted was material, but much less impactful than that seen from increasing SNSP, reducing minimum conventional generation levels and increased interconnection levels.

Conclusion 8

Energy limited storage technologies, such as batteries and pumped storage, have limited direct curtailment mitigation benefits on a high wind system. While conventional storage (battery and pumped hydro) has very little direct impact on curtailment, these technologies do have other potential system benefits that should be further explored, including providing fast frequency response, reserves, ramping and reactive power services, as an alternative to fossil fuelled peaking capacity and as a potential solution to local grid constraints.

Conclusion 9

Demand side management, including flexibility from EVs and heat pumps, has very limited direct curtailment mitigation benefits on systems with this level of renewable generation. We see the direct benefits increase somewhat if applied after other more effective mitigation measures. However, similar to storage, DSM does provide other important benefits to electricity systems with high RES-E.

Conclusion 10

By combining plausible levels of the mitigation measures, investigated in this study, it was shown that RES-E levels of 83% could be achieved while keeping curtailment below 5%. There are however several important caveats including:

- New interconnectors were assumed to export an average of 90% of their available capacity at times of surplus renewables. As interconnector flows are currently based on wholesale prices in neighbouring jurisdictions this outcome is not guaranteed. Further investigation is required to ensure that interconnectors will export near their rated capacity at times of high renewable generation in Ireland

- Removing operational constraints such that the proposed SNSP levels of 90% and min gen levels of 700MW, will require complex engineering analysis and solutions, combined with regulatory support for increased system services funding. Provided these levels can be reached the space that they create on the system is safe from a curtailment perspective, but the challenge of achieving this shouldn't be underestimated.
- Achieving a blended fleet capacity factor of 38% by 2030 is likely to be quite challenging given that most of the 2020 fleet is likely to still be operational in 2030. However, with some incentivisation, a blended capacity factor in excess of this level for of all new wind generation post 2020 should be achievable, both onshore and offshore. As the older fleet is decommissioned and re-powered post 2030, the full system benefits of higher capacity factors are likely to be realised.
- The benefits of DSM for curtailment and RES-E are greater when they are implemented after all other measures. The earlier mitigation measures have the effect of making curtailment more of a day/night problem and in these circumstances; DSM can start to have a more meaningful impact.

Conclusion 11

The 2040 analysis indicated that in simple terms, more of the same measures can get us to a 100% RES-E system. However over the timeframe to 2040 the uncertainties around some of these assumptions are higher. In particular, 90% exports on the interconnectors in circumstances when the entire EU market is likely to also be operating at very high renewable penetrations is certainly not guaranteed. At this time it is unclear whether the technical challenges associated with completely removing operational constraints could actually be overcome.

Conclusion 12

Between 2030 & 2040 Power-to-gas or Power to hydrogen technologies appear to have the potential to help bridge that gap both by absorbing significant volumes of additional renewable power and converting it to hydrogen or green gas for use in the heat and transport sectors, but also by enabling more installed wind capacity on the system resulting in additional RES-E being dispatched to the system during times of lower / more moderate wind speeds.

Existing market mechanisms do not capture certain system benefits that some technologies can provide, e.g. Power-to-gas, electrolysers, fuel cells, etc. If new technology providers are unable to monetise these system benefits then this will likely be a barrier to their deployment. It is important that market design (energy, capacity, system service & renewable auctions) keeps pace with technology evolution and national policy objectives to ensure that the system value provided new technology providers can actually be captured.

To provide solutions between 2030 & 2040 knowledge of Power-to-gas, electrolyser & hydrogen technologies must be gained now. We would strongly suggest this as an area for further study.

Conclusion 13

This curtailment analysis assumes the pro-rata allocation of curtailment across wind and solar generation on an all-island basis. This is consistent with the current SEM policy and dispatch of renewable generation by the System Operators. This policy may change due to the EU new Clean Energy Package. Included in the new regulations is the removal of priority dispatch for new renewable generators. At the time of publication of this report it is not clear how these new regulations will impact, if at all, on the overall levels of curtailment of renewable generation. After the impact of the Clean Energy Package on dispatch rules for renewable generation in Ireland have been determined it may be necessary that further curtailment analysis in complete for 2030.

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Appendix

Appendix A – Summary of Work Packages

Table 34 Summary of Work Packages

WP No.	Title
1.	Literary Review
2.	Develop and calibrate curtailment model
3.	Develop base case scenario
4.	Analysis the impact of SNSP and minimum conventional generation levels on curtailment levels
5.	Compare curtailment levels for varying capacity factors of wind generation
6.	Compare curtailment levels for wind and solar generation
7.	Analysis the impact of interconnectors and storage on curtailment
8.	Impact of the electrification of heat and transport on curtailment levels
9.	Feasible 2030 scenario
10.	Animation of 2030 Scenario
11.	2040 Scenarios Analysis
12.	Project Report
13	Communication and Dissemination

Appendix B – Heat Calculations

Schematic of Heat System

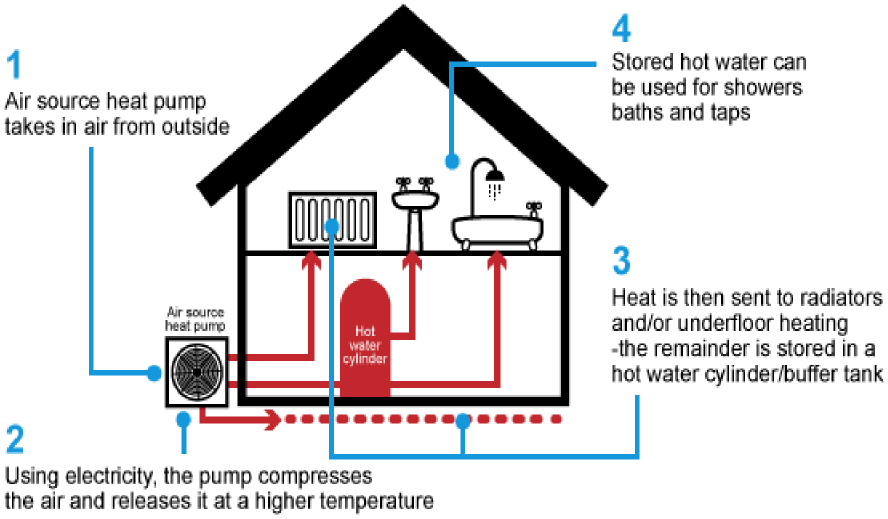


Figure 23 Schematic of heat system [35].

Heat Calculations

Area of cylinder

$$A_{cyl} = 2\,\pi\, r_{cyl,out}\, h_{cyl} + \ 2\,\pi\, r_{cyl,out}{}^2$$

$$A_{cyl} = 2\pi(0.355)(1.907) + \ 2\pi(0.355)(1.907)^2$$

$$A_{cyl} = 5.04\; m^2$$

Heat transfer co-efficient/U-Value for water cylinder

$$U_{cyl} = \frac{1}{R_{cyl} + R_i} = \frac{1}{\frac{l_{cyl}}{\lambda_{cyl}} + \frac{l_i}{\lambda_i}}$$

$$U_{cyl} = \frac{1}{\frac{1.907}{20} + \frac{0.08}{0.048}}$$

$$U_{cyl} = 0.60\; W/m^2K$$

Energy supplied to heat water from lower temperature limit:

$$Q = \ m_w c_{p,w}(T_{w,in} - T_{w,out})$$

$$Q = (500)(4186)(55 - 25)$$

$$Q = 62.79\; MJ$$

Electrical energy required to provide heat to one system:

$$q_i = \ Q\ \frac{1}{COP_{hp}}\frac{1}{3600}$$

$$q_i = (62.79 \times 10^6)\left(\frac{1}{3}\right)\left(\frac{1}{3600}\right)$$

$$q_i = 5.81\ kWh$$

Electrical energy required to heat all systems from empty, or the electrical energy storage potential of the system

$$q_{Total} = q_i \times N$$

Electrical demand from heat pumps in 2030:

$$Electrical\ Demand = q_{Total} \times N$$

Heat Profile Formulation (iii)

Heat Pump installed MW capacity

$$MW_{Cap} = \frac{Electrical\ Demand}{Hours\ in\ Operation}$$

Converting specific heat capacity to compatible units for calculating the temperature of water in cylinder

$$C = c_{p,w} \times \frac{1}{3600} \times \frac{1}{1000000}$$

$$C = 4186 \times \frac{1}{3600} \times \frac{1}{1000000}$$

$$C = 1.16 \times 10^{-6}\ MWh/kg°C$$

Temperature of water in cylinder throughout year, at hour i

$$T_i = T_{i-1} + \frac{(MW_{Cap} - MW_{i,Demand}) \times COP}{C \times m_w}$$

Appendix C – EV Profile

Profile based on a study carried out by Brady et al [36] was used as an input to the curtailment model. The study involved modelling charging profiles of electric vehicles based on real world data. In order to create a yearly profile at hourly resolution, the same 24 profile was applied for every day throughout the year. This assumption was necessary due to poor data availability in relation to electric vehicle charging and usage.

Vehicle statistics were accessed from the CSO [37], historical data indicated passenger cars travel 17,500km on average per year. While fuel consumption data on battery electric passenger cars was sourced from the SEAI website [38], the average fuel consumption was calculated to be 15.92 kWh/100km for all passenger cars available on the market. Vehicle projection numbers were in line with the 70 by 30 Baringa Study [8], which assume 629,398 electric vehicles on the road by 2030. Combining the distance travelled per year, fuel consumption and vehicle projection numbers – the MW profile for electric vehicles was formed with time dependency on the profile emanating from the Brady et al profile.

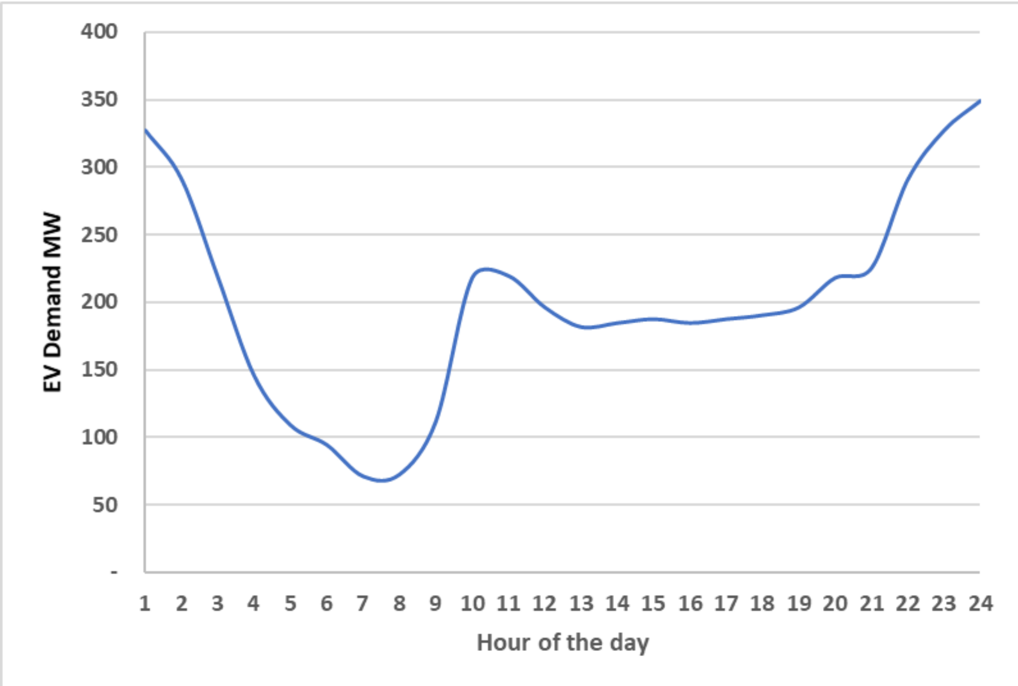


Figure 24 Average daily EV profile - 629,398 passenger cars.

Appendix D - Renewable Generation Profiles

Wind Profile

A blended hourly wind profile was created for the 2030 scenario analysis presented in this study. The profile captures the characteristics of both onshore and offshore wind. Offshore and onshore wind profiles for 2008 were sourced from EirGrid and combined to form the blended wind profile. The first step involved calculating a blended profile for the period up to 2020 with current onshore and offshore wind capacity factors employed. These capacity factors correspond to 31.04% and 36.54% for onshore and offshore wind respectively. The all island wind capacity for 2020 was extracted from EirGrid's 2018 GCS [7] to be 5600 MW. This figure consists of 4200 MW for the Republic of Ireland and 1400 MW for Northern Ireland.

The next step in the calculation was to create a profile for the timeframe between 2020 and 2030 to account for additional offshore and onshore capacity entering the system with higher capacity factors. The 2008 EirGrid profiles were again used to ensure consistency. An additional 4555 MW of all island installed wind capacity was forecasted in the EirGrid's 2018 GCS [7]. This projected amount is split into 3037 MW of onshore wind with a capacity factor of 37.5% and 1518 MW of offshore wind with a higher capacity factor of 42.5%.

Finally, both profiles were combined to provide a blended wind profile for inputting into the model. The capacity factor of the profile was calculated on a pro-rata basis to give an annual capacity factor of 33.96%.

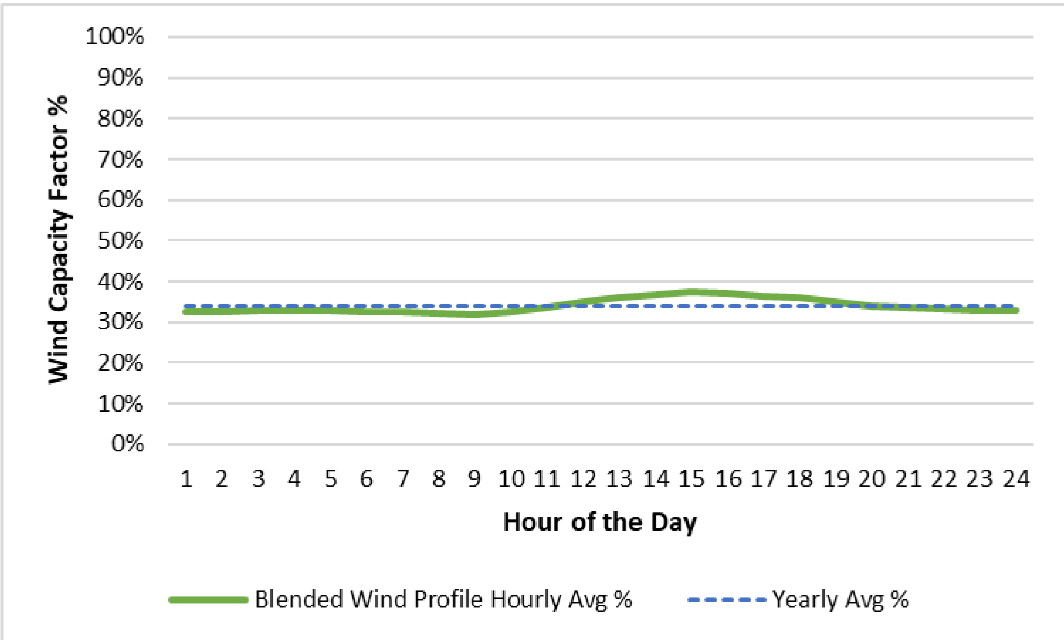


Figure 25 Average daily profile – Blended wind profile.

Solar Profile

A solar profile for 2008 was sourced from Mullan Grid's Database. The profile is based on a solar site in Co. Wexford with a capacity factor of 11%. It must be acknowledged that this profile is based on one site only and does not capture geographical variation for an all island system.

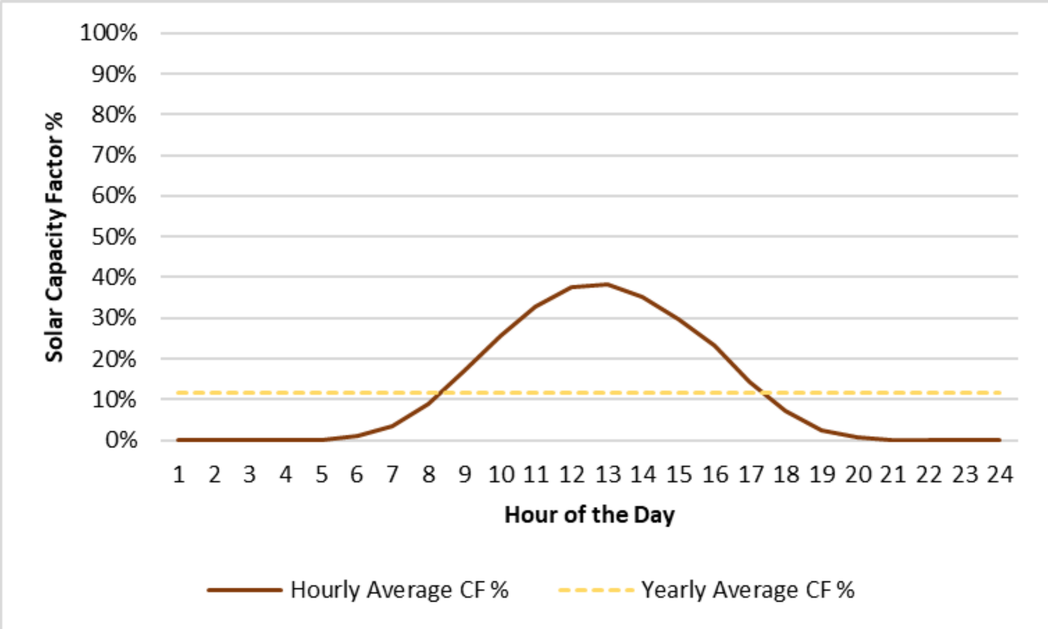
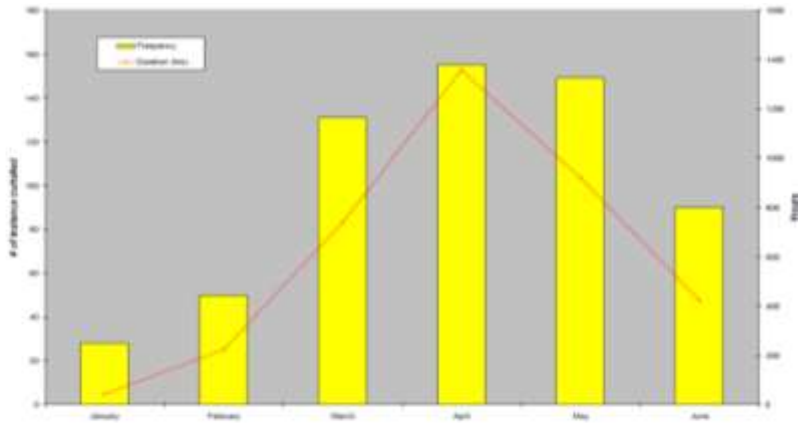


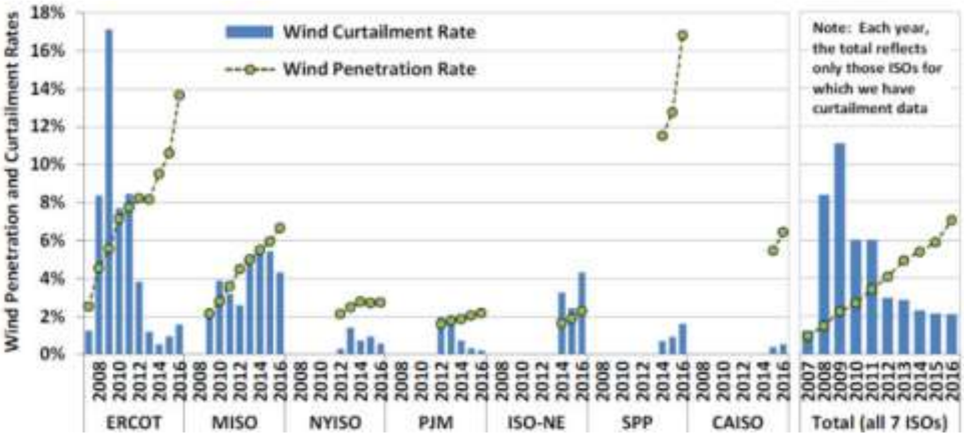
Figure 26 Average daily solar profile.

Appendix E – Curtailment in Various Regions

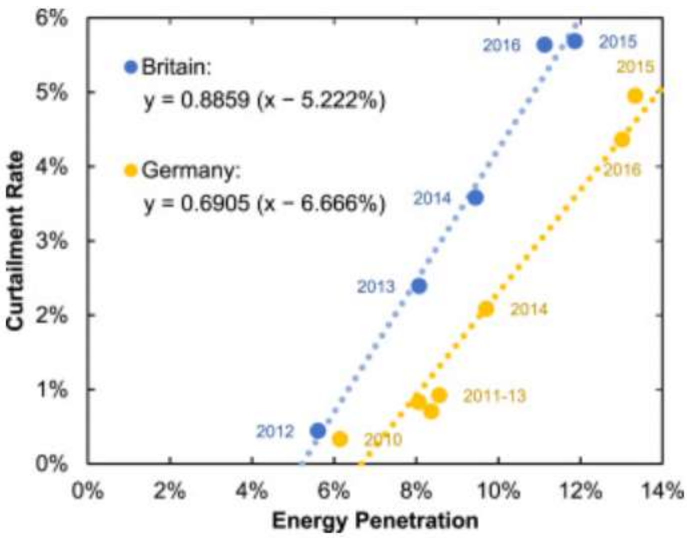
Curtailment affects in various Regions



(a)



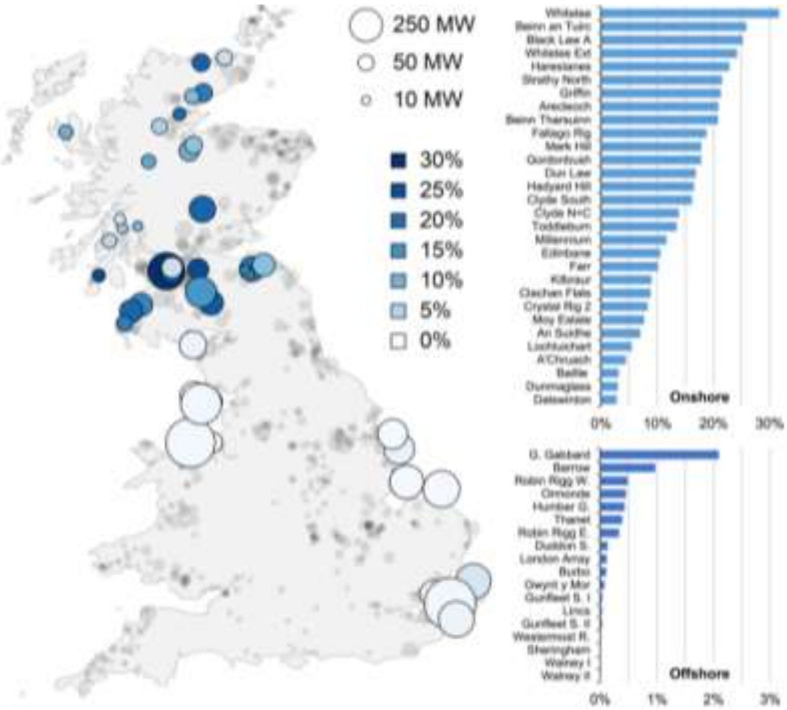
(b) [39]



(c)

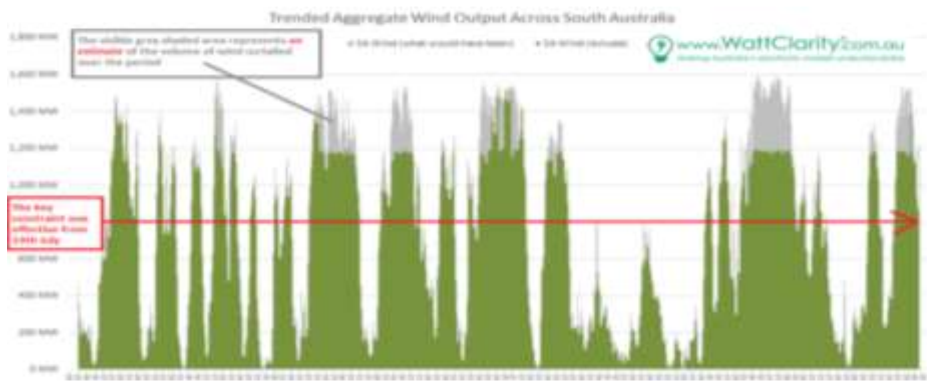
Figure 27 (a) US Frequency & Duration of Curtailment [40] (b) Penetration vs Curtailment US [39] (c) Penetration vs Curtailment UK & Germany [41].

Curtailment in other Regions



(a)

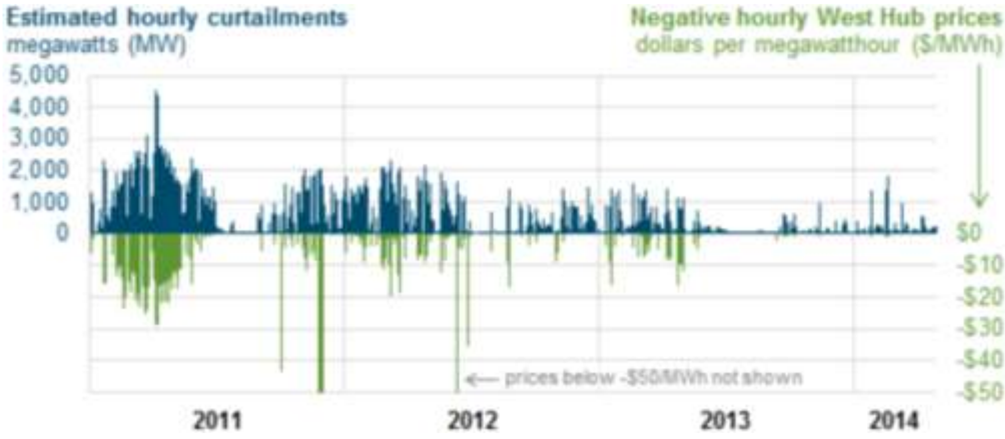
(b)



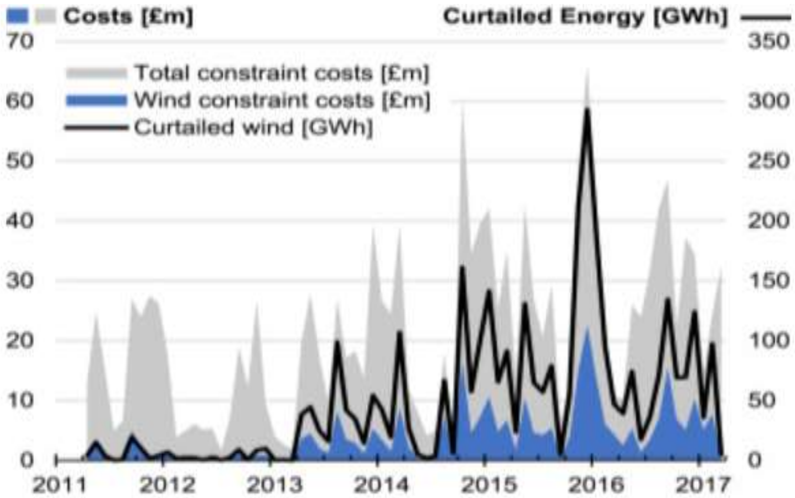
(c)

Figure 28 Curtailment Rates in (a) UK [41] (b) China [42] (c) Australia [43].

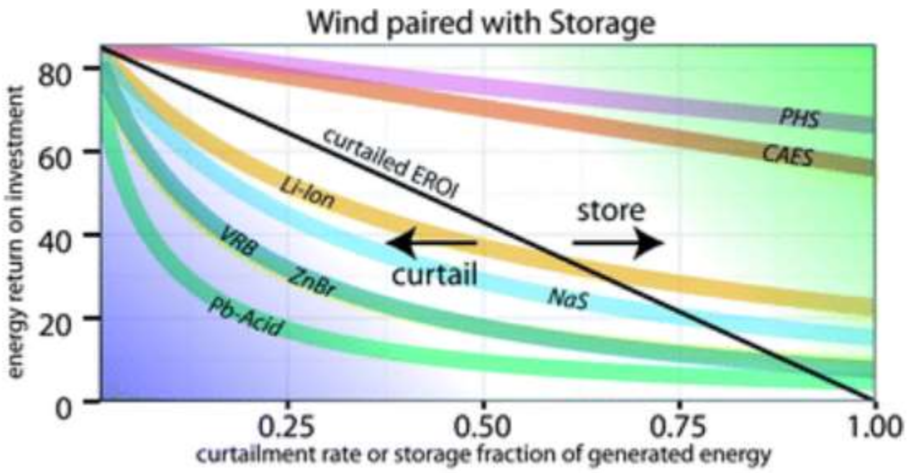
Cost of Curtailment



(a)



(b)



(c)

Figure 29 Cost of Curtailment (a) US [44] & (b) UK [41] (c) Implications with storage [10].

Appendix F – Energy Storage Technologies

Energy storage technologies

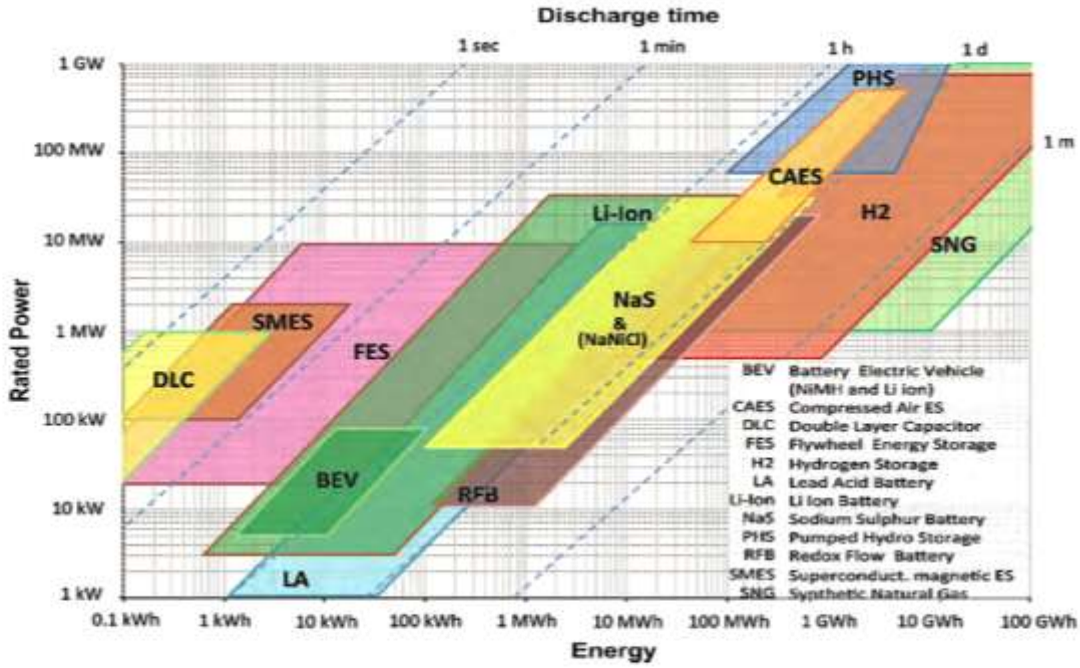


Figure 30 Comparison of rated power, energy content and discharge time of various EES technologies [40].

<u>**Pumped Hydro Storage (PHS)**</u>

- ✔ Stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation;
- ✔ Surplus off-peak electric power is used to run the pumps;
- ✔ During periods of high demand, the stored water is released through turbines to produce electric power;
- ✔ The plant is a net consumer of energy overall.

<u>**Compressed Air Energy Storage (CAES)**</u>

- ✔ Ambient air is compressed and stored under pressure in an underground cavern;
- ✔ When electricity is required, the pressurized air is expanded in an expansion turbine, driving a generator for power production;
- ✔ During the expansion phase, the high-pressure air must be heated, usually using natural gas fuel (generating carbon emissions).

<u>**Flywheels**</u>

- ✔ Work by accelerating a rotor to very high speeds and maintaining the energy in the system as rotational energy;
- ✔ The amount of energy stored in a flywheel is proportional to the square of its rotational speed;
- ✔ They typically experience far lower capacity than other storage applications.

Lithium Ion Batteries (LIB)

- ✔ Have the highest power density of all batteries on the commercial market on a per-unit-of-volume basis.

Sodium Sulphur Batteries (SSB)

- ✔ A very good option for energy management, but their greatest disadvantage is their cost.

Lead Acid Batteries (LAB)

- ✔ They are the most mature of all energy storage technologies that exist today;
- ✔ Attractive for their low cost and ease of manufacture;
- ✔ However, they present lower energy and power densities, and require a long charging time.

Flow Batteries (FB)

- ✔ Consist of two different electrolyte containers, as opposed to most electrochemical technologies, which use one container;
- ✔ Advantages include a longer lifetime and quicker response times;
- ✔ High manufacturing costs and more complicated system requirements compared to traditional batteries are disadvantages.

Thermal Energy Storage (TES)

- ✔ This technology consists of storing thermal energy by heating or cooling a storage medium;
- ✔ The stored energy can then be used later for cooling and heating applications as well as for power generation;
- ✔ Examples are the balancing of energy demand between daytime and night-time, storing summer heat for winter heating, or winter cold for summer air conditioning.

Superconducting Magnetic Energy Storage (SMES)

- ✔ SMES systems store energy in the magnetic field created by the flow of direct current in a superconducting coil;
- ✔ This coil must be cryogenically cooled to a temperature below its superconducting critical temperature;
- ✔ The stored energy can be stored indefinitely and released back to the network by discharging the coil.

Supercapacitors

- ✔ Store energy in an electric field;
- ✔ They have capacitance values much higher than other capacitors, but lower voltage limits.

Hydrogen

- ✔ High efficiency, energy and power densities;
- ✔ Can be converted to other chemicals for industry or other storage applications;
- ✔ Can enable sector coupling of electricity and gas; the ultimate solution.

Synthetic Methane

- ✔ The methanation process turns hydrogen gas into synthetic natural gas, which can be also injected into the grid;
- ✔ Like hydrogen, methane also has high energy and power densities;
- ✔ The methanation reaction can capture and utilise the CO and CO_2 produced by fossil fuels.

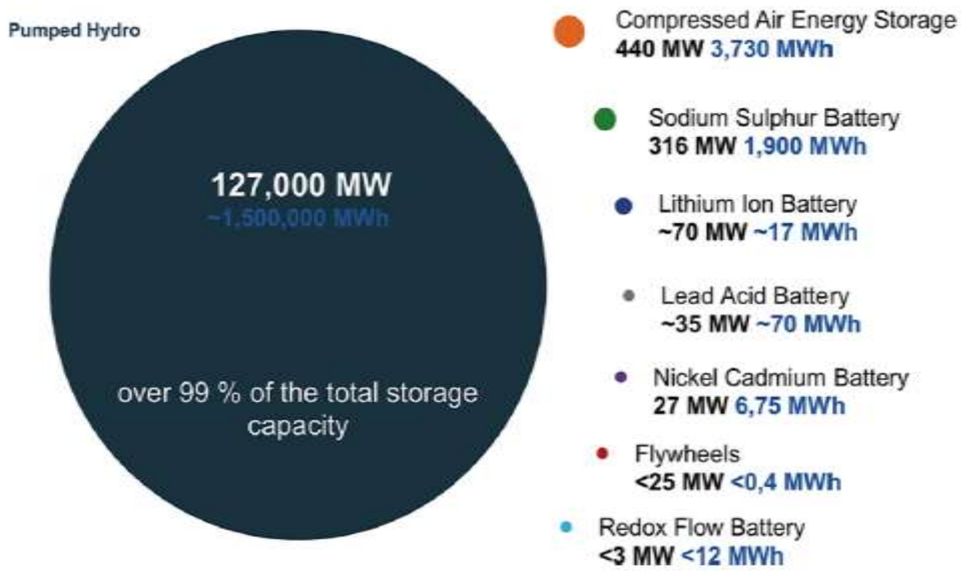


Figure 31 2010 Worldwide Installed storage capacity for electrical energy.

Table 35 Energy storage technologies

Technology	Type	Energy Stored	Power Output	Efficiency (%)	Readiness Level	Charge Time
Pumped Hydro Energy Storage (PHS)	Mechanical	High	High	75-85	Mature	min-h
Compressed Air Energy Storage (CAES)		High	High	60-80	Medium	min-h
Flywheels		Low	Moderate	85-95	Mature	minutes
Lithium Ion Battery (LIB)	Electrochemical	Moderate	Moderate	>90	Mature	min-h
Sodium Sulphur Battery (SSB)		Moderate	Moderate	85-90	Medium	hours
Lead Acid Battery (LAB)		Low	Low	80-90	Mature	hours
Flow Battery (FB)		Moderate	Moderate	70-75	Medium	min-h
Thermal Energy Storage (TES)	Thermal	High	Moderate	>50	Medium	min-h
Superconducting Magnetic Energy Storage (SMES)		Low	Moderate	>95	Early	minutes
Supercapacitors		Low	Moderate	>85	Medium	s-min
Hydrogen	Chemical	High	High	30-50	Early	Instant
Synthetic Methane		High	High	30-45	Early	Instant

Letters of Support