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Techno-Economic Analysis of Energy Storage within Network Constraint Groups for Increasing the Share of Variable Renewable Energy

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Abstract

To meet decarbonization targets, high levels of variable renewables (principally wind) have been connected to the Northern Irish electricity grid. However, wind generation has not been matched with integration solutions, which has led to high volumes of wind energy being dispatched down due to system stability issues and local network constraints. The deployment of energy storage portfolios within constrained areas to increase the consumption of variable renewables is assessed. Within constrained areas (constraint groups), storage portfolios are optimised using practical battery cost parameters to produce a range of portfolios that could alleviate constraints. The value streams that could make the deployment economically feasible are analysed, and the paybacks for the different deployment scenarios are obtained. In managing the variability of grid-integrated renewables, conventional network upgrades are cheaper under extant market arrangements but would only remove constraints: energy storage portfolios could eliminate both constraints and curtailments within each constraint group and could benefit from additional services through equitable market arrangements. In using the storage device for four-function services, the payback period certainly falls within the expected lifespan of the device; there are significant chances of having a payback period that falls within the expected lifespan when using the device for more than one service.

Techno-Economic Analysis of Energy Storage within Network Constraint Groups for Increasing the Share of Variable Renewable Energy

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ABSTRACT

To meet decarbonization targets, high levels of variable renewables (principally wind) have been connected to the Northern Irish electricity grid. However, wind generation has not been matched with integration solutions, which has led to high volumes of wind energy being dispatched down due to system stability issues and local network constraints. The deployment of energy storage portfolios within constrained areas to increase the consumption of variable renewables is assessed. Within constrained areas (constraint groups), storage portfolios are optimised using practical battery cost parameters to produce a range of portfolios that could alleviate constraints. The value streams that could make the deployment economically feasible are analysed, and the paybacks for the different deployment scenarios are obtained. In managing the variability of grid-integrated renewables, conventional network upgrades are cheaper under extant market arrangements but would only remove constraints: energy storage portfolios could eliminate both constraints and curtailments within each constraint group and could benefit from additional services through equitable market arrangements. In using the storage device for four-function services, the payback period certainly falls within the expected lifespan of the device; there are significant chances of having a payback period that falls within the expected lifespan when using the device for more than one service.

KEYWORDS: Constraints management, Energy storage policy, Locational storage value, Managing variable renewable energy, Northern Irish electricity grid, Storage market services

1. INTRODUCTION

The idiom "A job half-done is as good as none" reminds us that incomplete work can only deliver limited benefits – what could be done to bring electricity systems closer to sustainability has not yet been achieved because a critical piece of the puzzle is missing. While high levels of variable renewable generation (like wind and solar power) have been connected to electricity systems in recent years, we cannot say that it has been fully integrated because grid infrastructure and management has not evolved at the same pace. In many systems the variability of non-dispatchable renewable energy sources makes them subject to periodic restrictions because of certain network or system limitations, while in others energy storage techniques have been practically and successfully applied in controlling and capturing the variable renewable energy for later use.

A description of the features and applications of different energy storage systems is given in [1]. An account of battery energy storage projects within the UK, followed by the description and application of selected energy storage technologies, is given in [2]. In [3], the impacts of deploying energy storage on the level of curtailment and decarbonization are examined for different penetrations of renewables: it was observed that energy storage could substantially reduce the curtailments of renewables while also reducing CO_2 emissions to a level that depended on the level of contribution of conventional generators to the aggregated fuel mix. In [4], for a system with appreciable level of variable renewable penetration, an analysis was done on the benefit of energy storage deployment at different timescales. It was emphasised that energy storage is just one option out of the many methods available for handling variability or achieving high penetration of renewables.

In reducing the curtailments of wind energy, it is not economically advisable to deploy the storage only for curtailment-reduction purpose: it is important to include other revenue streams that would increase the value of the storage device deployed for managing variable renewables [5,6,7,8,9]. Jorgenson et. al. in [5] further suggested that, to fully realize the benefits of the variable renewables (wind generators) located at far distances from demand centres, an effective method is required to deliver the wind power at the right time, to the right location. Some works described the relationship between energy storage and forecasting improvements for variable renewable energy sources [10,11]. While forecasting has an important role to play in power system management, it might not be practical in sizing storage when the size of the deployed storage device is not expansible.

In [12], a technical and economic analysis was performed for five scenario curtailment-storage-penetration combinations: it was observed that, energy storage helps to increase the penetration of renewables but at certain levels of penetration, a no-curtailment level of storage leads to higher overall system cost in comparison to a system optimised with some curtailments. However, the analysis did not account for instances where other value streams are available to make the storage system less redundant, hence more valuable.

A power system that heavily relies on combined-heat-and-power plants could use a combination of pumped hydro storage and a portfolio of electric boilers to reduce the curtailment of wind [13]. Meanwhile, Sisternes et. al. in [14], while looking into the value of energy storage in decarbonization, suggested that, energy storage promotes the utilization of low-emission resources, large-scale deployment of battery storage would require cost reductions, and the marginal value of storage deployment declines with increasing level of storage penetration. In [15], the critical role battery storage could play in the Australian national electricity market in supporting the electricity grid is described with emphasis laid on the need to optimize the location of the storage device with respect to the cost of generation and transmission. As suggested in [16], a system operator aiming to achieve higher penetration of variable renewables will seek to understand the complexities of managing such system (like the Northern Irish electricity grid) having high levels of grid-integrated variable renewables.

One of the effects of having increased penetration of variable renewable energy resources is an increase in the level of demand for flexibility resources [17]; at the 110 kV level of the Northern Irish grid, battery storage is an important flexibility device. In [18], the benefits of battery hybrids in terms of achieving cost reduction, playing complementary roles, and providing additional value services are discussed.

This work describes how an electricity grid having high penetration of variable renewables (mostly wind energy) could be managed within network constraint locations – using energy storage portfolios – to increase the share of renewable energy in the aggregate fuel mix and provide an alternative to less-effective (in managing restrictions on variable renewables) conventional network upgrades. The Northern Irish electricity grid which is producing its electricity with more than 45% now coming from renewable sources annually (mostly from wind turbines) [19] and currently experiencing increasing levels of constraints and curtailments – having more than 15% of the total available wind energy in dispatch-down in the first two quarters of 2020 [20] – serves as a test case for deploying the storage portfolios. While accounting for the levels of the integrated variable renewables at the different sections of the grid with respect to network limitations, it becomes possible to deploy the storage device in constraint-level sizes within constraint locations, and have the device utilised for additional value services. The conditions under which the storage device could be deployed and the market arrangements that would make the storage deployment viable are described. The result reveals the net benefit of deploying storage devices as an alternative to conventional network upgrades.

1.1. Policy for Energy Supply:

With the increasing quest for sustainability and the desire to achieve Net Zero emissions for energy systems in many places; for example, in the UK where a Net Zero legislation has been passed [21] and with the report on climate action given in [22]: Net Zero should reflect in government policies; efforts must be increased towards connecting more renewables to the grid and managing the variability of the connected ones for sustainability. Specifically, in the UK where there is significant wind energy potential and expertise, the wind turbines ought not be restrained: new methods of maximising the use of the variable renewable energy resource must be developed to achieve Net Zero.

Operating under the Northern Ireland Assembly, the Department for the Economy (DfE) leads energy policies in Northern Ireland: working to develop energy infrastructure, support security of energy supply, and achieve an efficient and innovative energy system [23]. While energy policy is a devolved matter to Northern Ireland, in line with industrial directives aimed at reducing UK emissions, some fossil fuel-based plants (Kilroot coal-fired generators) are scheduled to operate at reduced capacity and some deficits in energy supply are anticipated [24]. With the closure of the Kilroot generators and without a second north-south interconnector to the all-Island system, Northern Ireland has a shortfall in generation capacity beyond 2025, under a "median demand" scenario [24]. New demands are also to be expected from electric vehicle uptakes with a ban placed on fossil-fuel vehicles in the UK by 2030 [25]. SONI's Tomorrow's Energy Scenarios Northern Ireland 2020 (TESNI) describes how the NI electricity system is to respond to the climate crisis, highlighting in [26]: renewable uptake scenarios, key challenges, and major opportunities. It is desirable to have real resource optimisation techniques that could help to maximise the opportunities of using the available variable renewable resources in NI while minimising risks.

Renewable energy policies such as the Northern Ireland Renewables Obligation (NIRO) (closed to new generation from 2017) [27] and progressive efforts by the system operator (SONI) and the network operator to keep more variable renewables in the electricity system helped to achieve the SEF target of having at least 40% of total electricity consumption coming from renewable sources in 2020 [19]. Meanwhile, SONI aims to further increase the SNSP close to 95% by 2030 [28], potentially allowing more variable renewables in the system.

Mass integration of renewable resources (wind and solar generators; storage and demand response devices) into the grid could change electricity economics substantially. In accounting for the equitable market conditions that must subsist to minimise risks and achieve a fair play amongst electricity stakeholders, another arm is included in the existing conundrum, giving rise to the electricity trilemma: maintaining a stable electricity grid, keeping emissions low, and having equitable electricity arrangement.

A future scenario electricity grid in places where a Net Zero emission target has been set is stable and reliable, delivers its electricity equitably such that there is consistently fair and impartial relationship between the electricity stakeholders, and the grid produces, transmits, and distributes its electricity following Net Zero emissions processes: depicted within the intersection of the circles of Fig. 2 [29].

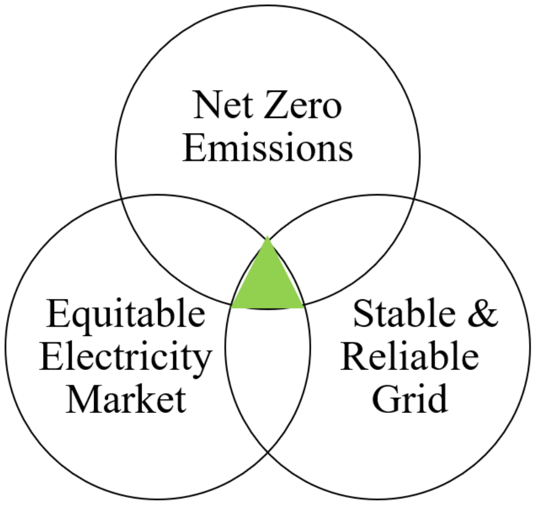


Fig. 2: Sustainability of Electricity Grid [29]

The market plans that would be required to ensure that storage and flexibility techniques could be deployed to support the integration of more renewable resources at the customer premise have been given in [29]. However, at the higher voltage end of the network (at 110 kV level) that is beyond the reach of customer premise devices and where there are certain constraints and curtailments of variable renewables, mass energy storage device could be deployed to reduce or eliminate the restrictions on the variable renewables; the storage device could also provide other valuable services through equitable markets.

1.2. Description of Electricity Grid:

The Northern Irish (NI) electricity grid is made up of a few synchronous generators, some small dispatchable generators, and up to 1314 MW existing and committed non-synchronous variable renewables: with transmission networks at 275 kV and 110 kV, distribution networks at 33 kV and 11 kV, several substations for signal controls and energy redistribution at different voltage levels, terminating at different end user loads. The grid also has limited interconnection to neighbouring grids for cross-border electricity trading and for increased grid resilience [24,30].

1.2.1. Composite Characteristics

The synchronous generators currently contribute significant power to the grid, helping the power system to achieve a required level of system inertia: having such generators connected to a system helps to prevent the system from experiencing abrupt changes in frequency [31]. However, when the synchronous generators run with fossil fuels, including them in the grid also means increased greenhouse gas emissions. Here, the synchronous generators run with either gas, oil, or waning quantities of coal, typically making up to 50% of the total fuel mix annually [24].

To increase the share of renewable energy in the fuel mix for sustainability, several renewables – mostly wind turbines – have been connected to the electricity grid [24]. Since 2020, about 49% of electricity consumption comes from renewable sources, mostly from the wind turbines [19]; this signifies the achievement of an early renewable energy target set in 2010 through a Strategic Energy Framework (SEF) – a guidance policy for energy in Northern Ireland [32]. While some of the renewables are connected at the 11 kV and the 33 kV segments of the electricity grid, others (large power wind and solar farms) are linked to the higher voltage end of the grid through 110/33 kV substations [30].

Meanwhile, as noted in [33], the increased connection of the variable renewables leads to unintended consequences, putting strain on the relatively small NI grid. While the total installed capacity of synchronous generators is about 2400 MW, the level of connection of variable renewable generation (wind and solar PV) to the grid has significantly increased, especially from 2014: the total (small- and large-scale generations) installed capacity in 2019 being over 1400 MW. Whereas peak electricity demand is about 1819 MW, typically occurring around winter months [24]. The NI network operator and the system operator aim to make the grid function in an increasingly sustainable, safe, and secure manner [24,30].

1.2.2. Curtailments and Constraints of Grid-Integrated Renewables:

In similar manner to large synchronous conventional generators, variable renewables are often connected to the electricity grid such that their generated supplies are fed to power loads at different parts of a network. While the variable nature of the power supply from the renewables is a major challenge, efforts are consistently being made to integrate more of the renewables to the grid because of their lower carbon footprints. While the dispatchability and large-power-generation capabilities of large fossil fuel plants are desirable, the clean nature of wind turbine and solar power generators wins the heart with respect to energy sustainability. Many electricity systems seek a balance between operating certain synchronous conventional energy generators while keeping some renewable supplies, switching off the desired renewables occasionally to maintain a qualitative functionality of the grid.

With respect to the NI electricity grid: constraints could arise when the thermal rating of the transmission circuit in a particular area is exceeded, or when additional power flow from wind or solar generation would cause voltage instability – as the proportion of reactive power drops as a result of increasing active power from say wind turbines, voltage could sag – or when the level of power flows from any variable renewable is such that tripping of a transmission equipment would result in overload of any network element, and/or when a section of the power network is to undergo maintenance and keeping variable renewables at certain safety level is required [34]. Whereas curtailments (which are system and global safety mechanisms) have arisen from maintaining a technically safe level of System Non-Synchronous Penetration (SNSP) – the System Operator for Northern Ireland (SONI) determines what level of non-synchronous generation the system should safely accommodate, up to 65% in 2020 [28] and a trail on 70% SNSP in place [34]. Another reason for curtailments has been that of maintaining the required level of inertia in the system for frequency stability [35].

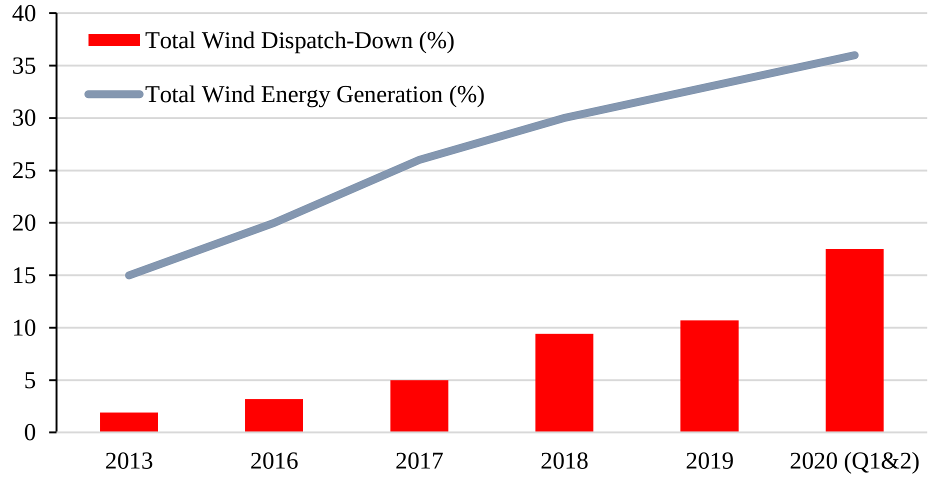


Fig. 1. Annual Wind Dispatch-Down and Wind Energy Generation

Between 2013 and 2020, the total energy generation from wind rose from 15% to over 35%; within the same period: In 2013, 1.9% of the total available wind energy was dispatched down; the dispatch-down was 3.2% in 2016 [36]; it was 5% in 2017 [37], 9.4% in 2018 [35], 10.7% in 2019 [38], and over 15% in the first two quarters of 2020 [20], Fig. 1. A typical aggregation and breakdown of wind dispatch-down for each month in a year are given in [35], with the largest volumes occurring during winter months.

1.3. Grid-Integration of Energy Storage Devices:

It is established that certain energy storage techniques could be used to capture variable renewable supplies for control or later usage. Some of the storage technologies include lead acid battery, lithium-ion battery, flywheel energy storage, flow batteries, compressed air storage, pumped hydro storage, and fuel cell techniques. An account of the features of the major energy storage technologies has been given in [1]. With the increasing integration of variable renewables, different energy storage techniques become valuable for certain flexibility opportunities: when the storage device is connected to the electricity grid, it could provide certain services across the electricity supply chain. To mention just a few: self-consumption of energy, energy arbitrage, ancillary services to support the grid, demand response, time-of-use-electricity-bill-management, among others. Some of the services help in achieving improved grid resilience while others provide economic benefits to different electricity stakeholders.

As illustrated in Fig. 3, the gap between maximum wind energy generation and minimum system demand for Northern Ireland in 2019, given in [38], is a value region where large part of the constraints and curtailments take place: the gap presents considerable energy storage opportunity for maximising the use of the available wind energy resources. The opportunities are noticeable around winter months and significant through the months of the year.

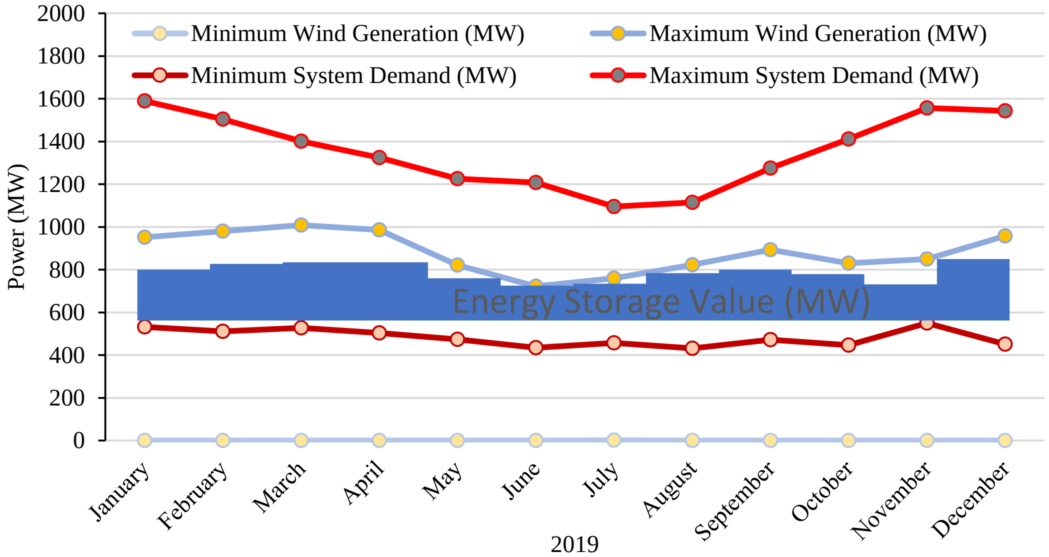


Fig. 3. Illustrative Wind Energy Generation and System Demand Showing Energy Storage Opportunity

2. ENERGY STORAGE WITHIN CONSTRAINT GROUPS

As discussed under subsection 1.1.2, sometimes it becomes necessary to restrict power flow from grid-connected variable renewables. While curtailments are system-wide restrictions, constraints are local restrictive limitations within an area of the network. Generators and other electrical network elements connecting within the same area will typically belong to the same constraint group: the generators will typically first feed any output power to other segments of the electrical system through an immediate network. One or more generators connecting to the same local station will also typically share the same network elements.

2.1. Constraint Groups:

The constraint group for an area reflects the impact the generators within the area have on the network equipment within the same area. A generator that does not have an impact on the local network could be excluded from the local constraint group: if the generator (also) has an impact on another network area of the grid, it should (also) belong to a constraint group in that other area of the grid. Other generators in other areas connecting directly to other immediate networks, or generators in a local area bypassing the local network by connecting directly to another network area must belong to another constraint group, different from the local constraint group of the local area.

Considering how network topologies and equipment affect constraint grouping: when there is a change in the network arrangement of an area – for example, installing another power line with an existing line – there could be new possibilities of power flows; the constraint grouping could become different. Similarly, new connection of generators to a local network within an area could significantly change the impact of the existing equipment on the network of the area. These imply that constraint grouping could be a continuous analysis: elements could be added or removed from constraint groups as new updates emerge, and as the grid undergoes major maintenance or upgrades.

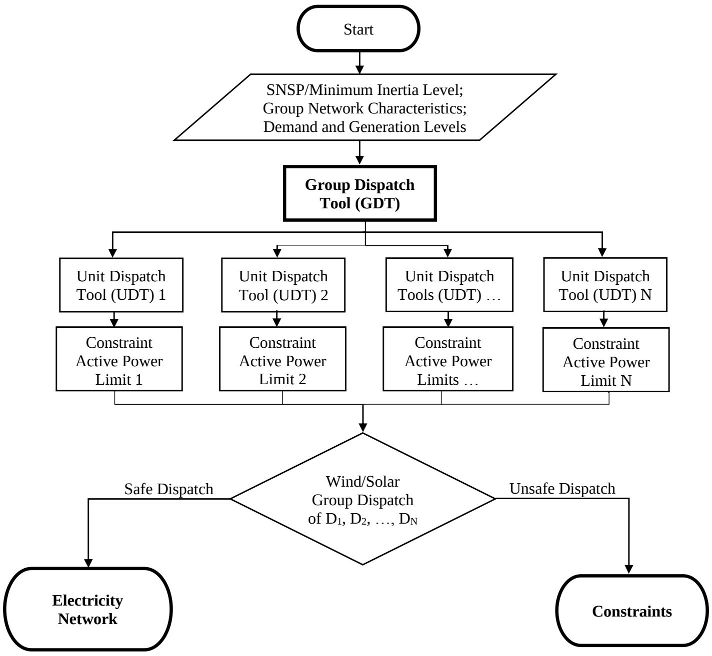


Fig. 4: Flowchart Illustrating Variable Renewable Dispatch Within A Constraint Group

Looking at the illustrative variable-renewable-dispatching flowchart of Fig. 4, a Group Dispatch Tool (GDT) takes as input the local and system parameters: SNSP level, inertia level (for curtailments leading to constraints), the group network characteristics, temperature, network topology, local power demand and generation levels, any planned activity, and any contingencies; determines if there is any need for constraint at the subsisting generation level; and if there is need for constraints, calculates the proportion of the current active power of variable renewables to be dispatched. Without a storage mechanism, through the signal inputs to each of the Unit Dispatch Tools (UDT), any unsafe levels of renewable generation are dispatched down – constrained.

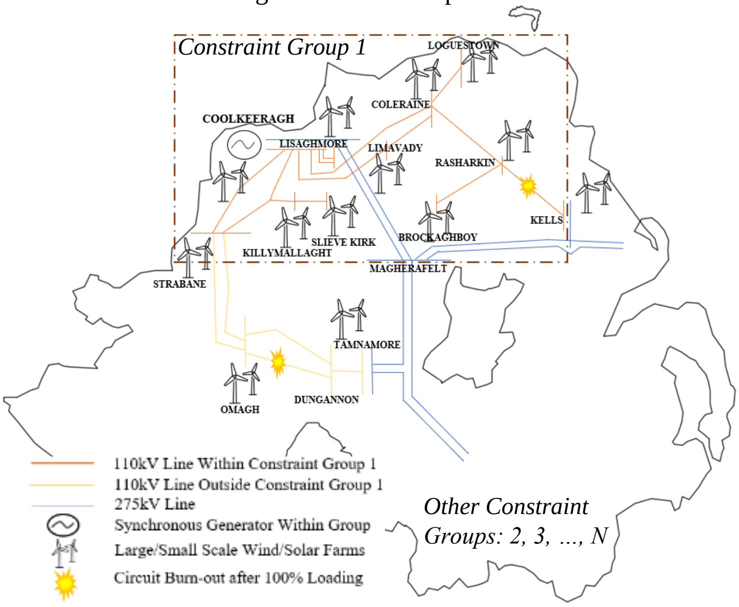


Fig. 5: A Constraint Group within Electrical Network [30,39]

Looking at how the constraint group dispatching works on the NI grid: Fig. 5 [39] represents a section of the electricity grid in a high wind area. Within the area there is a high-power synchronous generator and a few variable renewables (mostly large-scale wind turbines and solar farms) connected through the 110 kV transmission network at different stations – ten stations (Brockaghboy, Coleraine, Coolkeeragh, Killimallaght, Limavady, Lisaghmore, Loguestown, Rasharkin, Slieve Kirk, and Strabane). While a lot of renewable generation happens within the area covering the ten stations, the bulk of energy demand happens around the eastern network area, beyond the Kells station: a major network limitation is thermal overload of the 110 kV transmission line linking station Rasharkin to the station Kells – representing constraint group 1: the main source of electrical constraint within the constraint group 1 network [36,39,40]. The details on the source of constraint for other constraint groups are given in [40].

While it could be difficult to have a power system that would not restrict power inflow from variable renewables in any way, for sustainability, it is important that any restricted clean supply be captured and re-utilized effectively rather than dispatched down and wasted. One way of increasing the share of variable renewables is capturing and reusing the excess power flows that would be restrained by deploying energy storage techniques. Constraint grouping helps in determining the location and effective size of storage.

2.2. Storage Deployment:

Describing the dispatch within constraint groups with storage arrangement as depicted in Fig. 6: a Wind Dispatch Tool (WDT) takes the global and group parameters (SNSP level, inertia level, network characteristics, any planned activities or contingencies, demand and generation levels), determines if there are any needs for constraint at the subsisting generation levels of each group; if there is need for constraint, calculates the proportion of the current active power of the renewables to be dispatched for each group, and subsequently for each generating unit. With a storage mechanism designed for each constraint group, any unsafe level of renewable generation feeds the storage device: the excess flows from the renewables are channelled through a path of energy capture and reuse.

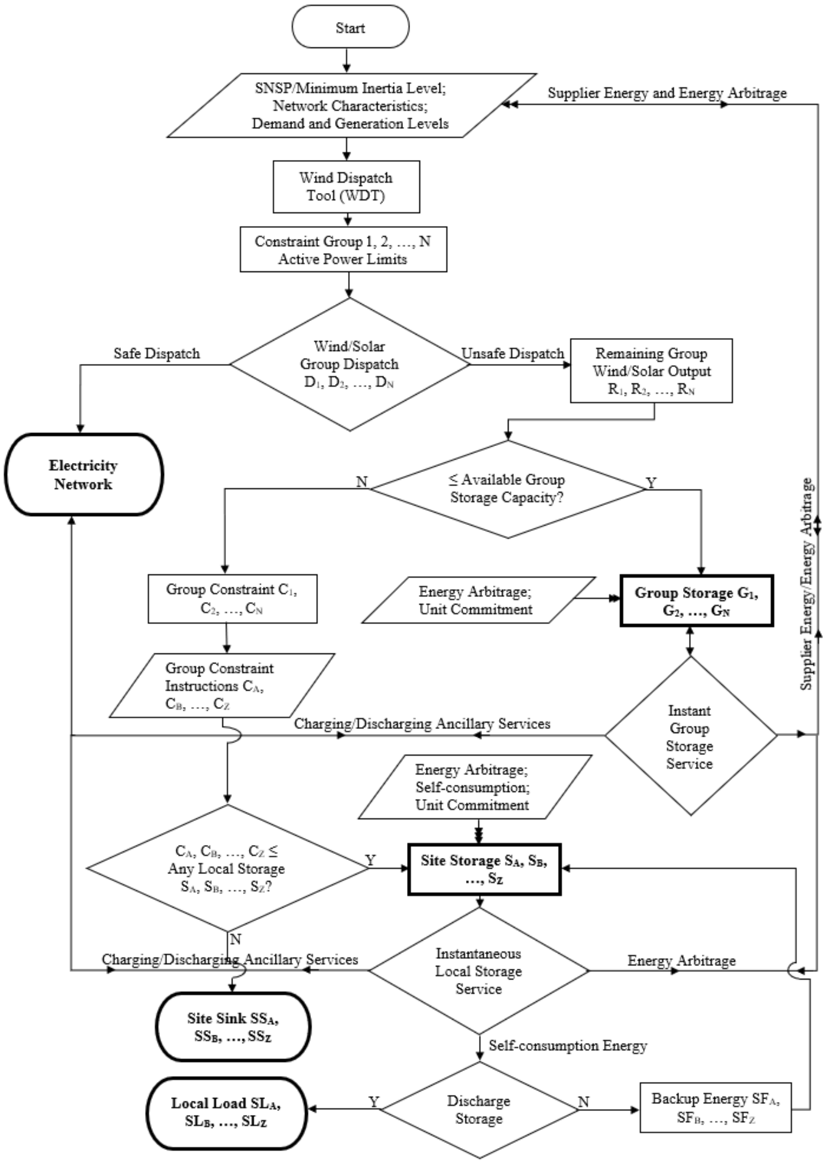


Fig. 6: Dispatching Variable Renewables Within Constraint Groups with Energy Storage

There are different scenarios for storage, depending on the group or local storage equipment: when the excess power flows from the renewables fall below any available group storage capacity, the storage device is prompted to take up the excess flows, Fig. 6. The group storage device receives instructions for dispatchable supply, arbitrage energy, and/or any unit commitments to providing ancillary services: the instructional codes determine when and how (whether charging or discharging) the device will respond at every instance. Meanwhile, when the excess power flow from the renewables is above the group storage capacity, the storage device cannot take up the excess flow. The excess flow must follow the path of local constraint where it would be processed to determine when a local site device is available to capture the local inflow, the instructional processes must happen within microseconds.

When a site storage mechanism is available, any excess power inflow is captured. The site storage device receives instructions for arbitrage energy, self-consumption energy, and/or any unit commitments to providing ancillary services: its instructional code instantaneously determines when and how it discharges any captured energy. However, when a storage device is not available, the renewable generation system follows the path of a lossy power operation: the output of the renewable generator could be restrained or have its unrestrained excess generation fed into a power sink on site, Fig. 6.

Some of the important factors that must be considered while deploying the storage device in preventing the constraints of variable renewables includes the location of storage, the size of storage, and the time of the device deployment with respect to any services to be provided.

2.2.1. Location:

The storage must happen within the constraint groups: the storage device is localised such that it is able to take up any excess power generation from the renewables, meaning it must be accessible to the potentially constrained renewable generators within the group. Moreover, the device must be located before the point of constraint within the group; for example, the group storage for the constraint group 1 (Fig. 5) must be situated at a location before the Rasharkin-Kells power line so that any excess power from the variable renewables in the west would not have to flow through that line, the captured excess power could be supplied through the system when it is safe.

The storage device should also be situated where it could be connected to deliver its pre-determined service values; for instance, if a storage device is to be deployed to prevent constraints of renewables while also providing energy arbitrage through the Irish Integrated Single Electricity Market (ISEM), then the device should have a suitable connection to the all-Island transmission network where the ISEM currently takes place [41]: this could also require that the device be of certain minimum standards, depending on the nature of the interconnection that is to exist between the device and the grid.

2.2.2. Size:

The size of a storage device could be defined in terms of the power (kW or MW) rating or the energy (kWh or MWh) rating. While the power rating indicates how much signal (current and voltage) the device could deliver at every second, the energy rating indicates the length of time the device could deliver the rated power when fully charged. Meanwhile, deploying a higher energy capacity or higher power rating storage device could mean higher capital costs of storage. In deploying the storage device for capturing excess renewable flows, the projected level of constraint indicates the size of storage required. The capacity for storage could be optimised to largely remove any local constraints, use any seasonal excess capacities for deriving energy values, and leverage any suitability of the storage technology in providing concurrent ancillary services.

Nevertheless, to totally avoid constraints, the storage capacity must be higher than any instantaneous level of constraint within the constraint group – the availability of the storage capacity hence ability to eliminate constraints will also depend on the presence or absence of priority discharge. The minimum aggregated capacity of storage required in MWh ($S_{Z(\min)}$) is given as:

$$S_{Z(\min)} = \sum_{0}^{n} (W_n \times h_n) \tag{1}$$

where W_n is the constrained active power in MW for each instance, h_n is the duration of constraint in hours for each instance within electricity trading interval from zero to n.

$$A_{C(n)} \propto S_{Z(\min)} \tag{2}$$

where $A_{C(n)}$ is the available aggregated storage capacity of constraint group in MWh at the instance n.

$$A_{C(2)} = A_{C(1)} - \sum_{0}^{1}(W_n \times h_n) \pm \sum_{0}^{1} S_n \tag{3}$$

$$A_{C(n)} = A_{C(n-1)} - \sum_{0}^{n-1}(W_n \times h_n) \pm \sum_{0}^{n-1} S_n \tag{4}$$

where $A_{C(1)}$ and $A_{C(2)}$ are the available aggregated storage capacities of the constraint group in MWh at instances one and two respectively, W_n is the constrained active power in MW for each instance, h_n is the duration of constraint in hours for each instance within electricity trading interval from zero to n, and S_n denotes the energy response through charging/discharging for ancillary services within the trading interval between zero to n.

Not least, the individual storage units must be distributed in proportionate sizes with respect to the constraint group network such that the operation of any of the devices within the network would not in itself constitute another major constraint, especially constraints arising from the thermal ratings of constituent network elements.

2.2.3. Time:

As discussed under subsection 2.2.2, the projected level of constraint usually suggests the size of storage required, suggesting that having a higher constraint projection for say winter would mean higher storage requirement during winter months. It could, however, be impractical to occasionally expand the storage size for different seasons of different storage requirements. However, the storage capacity could be put to optimal use through opportunistic services: energy arbitrage through ISEM during low and negative electricity price times of the day (usually occurring during special windy-hour baseload times at night) and through the provision of ancillary services to the electricity grid. Meanwhile, in the future, hydrogen production, compression, and storage would provide another utility possibility: where end user loads could not directly connect to the electricity grid, the excess electricity from the renewables could be used in producing hydrogen which could be stored away through seasons.

2.3. Power Network Stability:

It is important that the deployment of any storage device does not compromise the stability and reliability of the electricity grid: the size of the storage device must be appropriate with respect to the other elements in the adjoining node, the storage technology and controls should be reliable, and the distribution of the storage units within each constraint group should be of a convergent and stable power flow. And after deploying the storage device, the power flow run within the network must converge. The system operator uses the WDT to coordinate the network outside of the storage space. More discussion around conducting a technical analysis on a modified network is given in [42]: for a convergent and stable power network, the real (P_i) and the reactive (Q_i) power components within a bus *i* are respectively:

$$P_i = V_i \sum_{k=1}^{n} V_k Y_{ik} \cos(\theta_{ik} + \delta_k - \delta_i) \tag{5a}$$

$$Q_i = -V_i \sum_{k=1}^{n} V_k Y_{ik} \sin(\theta_{ik} + \delta_k - \delta_i) \tag{5b}$$

where V_i is the voltage across the *i*th bus, V_k is the voltage across the *k*th bus, Y_{ik} denotes the mutual admittance between the *i*th and the *k*th nodes, *n* represents the number of buses within the network, δ represents the load angle, and θ is the phase angle between current and voltage.

2.4. Market Analysis for Battery Storage:

While the desire to minimise clean energy wastage and increase the share of renewable energy in the energy mix (for a more sustainable electricity system) may be leading efforts towards deploying energy storage device, as discussed under subsection 1.3, achieving sustainability also means that the storage device must be deployed such that the electricity grid works within equitable arrangements. Hence, the different sources of value that could help to maximize the benefits of storage must be identified.

Of the different storage technologies available, lithium-ion battery is chosen for the economic analysis. The lithium-ion battery is chosen because it has appreciable energy density, it could be controlled for quick swings between the charging/discharging states, it could withstand deep discharging, it has fast frequency response, it has appreciable round-trip efficiency, and the technology is relatively reliable and mature [1]. Moreover, there are practical instances where the battery technology has been successfully deployed to perform multiple storage services to the customer and to the electricity grid [2]. Another example of such deployments is the 1.11 MW/2.15 MWh Tesla Powerpack 2.5 lithium-ion battery deployed by the University of Queensland (UQ) to reduce energy costs and generate revenue [43]. Here, the parameters of the UQ's lithium-ion battery, given in [43], are used for the economic estimations: the detailed parameters of the battery are given in Table A.1 and Table A.2 of Appendix A. Different cases of putting the battery into use are analysed.

Meanwhile, to account for the cost dynamism of battery technologies – the cost of battery is projected to decrease with time as economics of scale from mass production activities further drive down costs [44] – lower battery cost parameters are selected to reflect the possible future scenario of storage payback period, the payback period being the aggregated storage cost divided by the annual revenue from storage.

2.4.1. Case 1: Storage Deployed to Prevent CC and for Self-Consumption Energy:

A battery storage could capture excess power flow and prevent the Constraint or Curtailment (CC) of renewables while using the captured energy at the local site or transported to other points for consumption. Electricity price is taken as £0.15/kWh [45,46]. The gain in using the storage device for self-consumption energy (SC_{sc}) is estimated:

$$SC_{sc} = E_{cc} \times \eta_{bat} \times P_{sc} \tag{6}$$

where E_{cc} is the total excess energy inflow from renewables, η_{bat} is the round-trip efficiency of the battery storage system, and P_{sc} is the consumer electricity price.

2.4.2. Case 2: Storage Deployed to Prevent CC and for Supplier Energy:

The battery storage could also be deployed to capture excess power flow and prevent the constraint or curtailment of renewables with the captured energy supplied through the electricity grid later. Using the Second (auction) Intra-Day Market (IDM2), the average selling price of energy is taken as £49.76/MWh [47]. As discussed under subsection 2.2.1, the storage device must be localised where it could connect to deliver its stored energy. The gain in using the storage device as an energy supplying device (SC_{sc}) is given as:

$$SE_{se} = E_{cc} \times \eta_{bat} \times P_{se} \tag{7}$$

where E_{cc} is the total excess energy inflow from renewables, η_{bat} is the round-trip efficiency of the battery storage system, and P_{se} is the average electricity selling price.

2.4.3. Case 3: Storage Deployed for Energy Arbitrage Services:

Certain capacities of the deployed storage device could be used in purchasing bulk electricity at lower prices; the obtained energy could be sold to the grid at higher prices for profit. The device must be able to access the electricity trading market – ISEM. The gain in using the storage device for energy arbitrage (EA_{se}) is given as:

$$EA_{se} = E_{cp} \times \eta_{bat} \times P_{net} \tag{8}$$

where E_{cp} is the total volume of energy traded, η_{bat} is the round-trip efficiency of the battery storage system, and P_{net} is the net electricity purchase price.

2.4.4. Case 4: Storage Deployed for Ancillary Services:

One of the reasons for seeking to deploy a storage device with a fast response to charging or discharging is to allow such device to provide voltage and frequency supports to the grid. For the NI electricity grid where there is a pioneering proportion of grid-connected variable renewables, the "Delivering a Secure, Sustainable Electricity System" (DS3) programme was designed by the system operator to allow eligible units to commit certain capacities to providing frequency response, ramping margin, and classified reserve supports to the grid [48].

The basic payment rates of main storage eligible DS3 services are given under Table B.1 of Appendix B. In providing some services, the storage device could be required to be charged or discharged. The gain from committing certain capacity of the storage unit for the DS3 ancillary services (CS_{sc}) is given as:

$$CS_{sc} = \frac{1}{2} \times C_{cp} \times \%_{bat} \times P_{DS3} \tag{9}$$

where C_{cp} is the total capacity of the storage device, $\%_{bat}$ is the percentage of the total capacity of the storage device committed to providing the DS3 services, and P_{DS3} is the aggregated price of all the DS3 services the device has been committed to provide.

2.4.5. *Case 5: Storage for Multiple and Stacked Miscellaneous Services:*

As shall be discussed in subsequent result section, at times, it would be necessary to utilise a storage device for multiple or stacked services in addition to using the storage devices for preventing CC: to make the deployment of the storage device economically feasible, the device may have to be utilised opportunistically for value. This is especially so because the required storage portfolio deployed to prevent CC might be redundant at certain times of the year whereas valuable services are often available for the devices to benefit from; for example, the DS3 services, the energy arbitrage services through ISEM, and a combination of some of the services for achieving shorter payback periods on storage investment.

The gain in using the storage device for stacked or multiple services ($SCEA_{sce}$) is estimated:

$$SCEA_{sce} = SC_{sc} + SE_{se} + EA_{se} + CS_{sc} \tag{10}$$

where SC_{sc} is the self-consumption energy gain, SE_{se} is the supplier energy gain, EA_{se} is the arbitrage energy gain, and CS_{sc} is the DS3 ancillary service gain.

Meanwhile, the use of storage within constraint groups has been focused on the higher voltage ends of the electricity network, beyond customer premises.

2.5. *Storage and Flexibility Techniques within Distribution Network Areas:*

While a case is being made for battery storage deployed within the constrained areas of the 110 kV electricity network, there are other areas of the network where the techniques discussed could be applied to support increased consumption of variable renewable energy, especially at the locations where different consumer-premise flexibility and storage devices could connect to the network. In [42], through an 11 kV substation of a campus distribution network, a 2 MW/4 MWh storage was deployed to increase self-consumption of wind energy; new wind turbines and batteries were simulated for flexibility gains within the distribution network in [49]. Demand response strategies have been described to manage network congestions while providing ancillary services through the network using different levels of load portfolios in [50], moving loads from peak to off-peak periods in [51]; and residential batteries are described for peak shaving in [52].

As the transitioning to clean energy technologies continues through electrification of transport and heating processes, demand flexibility through heat pumps and thermal storage could manage wind power [53,54]. Electric vehicles and heating processes represent additional loads that could be managed with storage and flexibility techniques. The tariff designs and policies that will create an equitable market in support of utilising more wind and solar resources towards achieving sustainability of the electricity grid with the storage and flexibility techniques are described in [29]. And essential standardised resource management tools have been highlighted in [55].

3. RESULTS AND DISCUSSION

A ‘perfect’ constraint grouping for the 110 kV network of the NI electricity grid is depicted in Fig. 7 [40]. There are four major constraint groups in all. As could be observed from the Fig. 7, a constraint group could be a subset of another larger constraint group: constraint group 3 is a subset of constraint group 2, constraint groups 1, 2, and 3 are subsets of constraint group 4 – the constraint group 4 represents all-NI 110 kV network constraint [40].

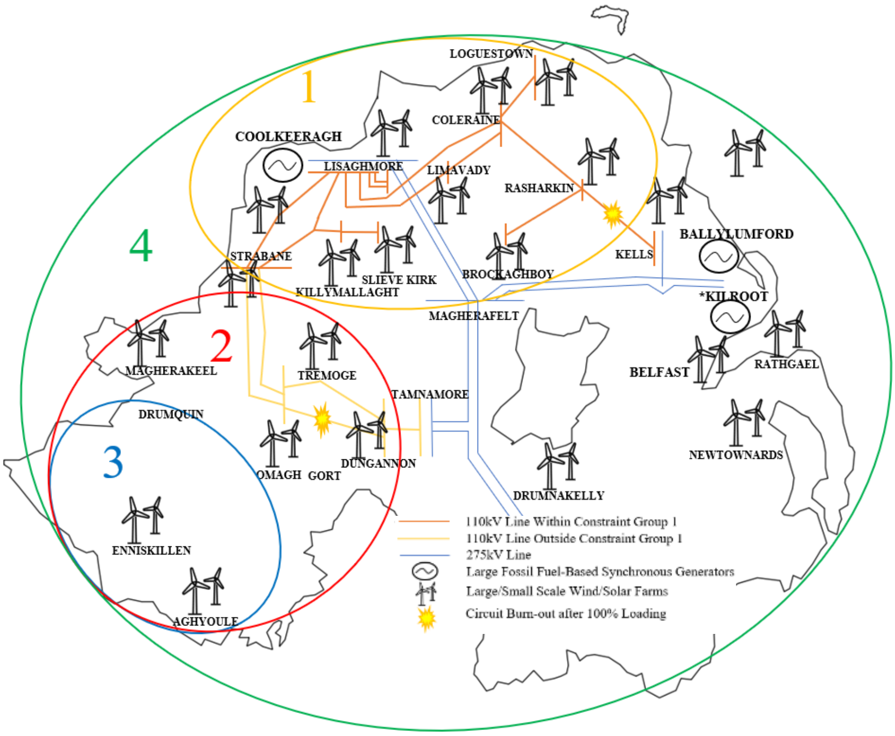


Fig. 7: 110 kV Network Constraint Groups [30,39,40]

With the constraint groups, local resources are installed within the local network to manage the group constraints. Without the constraint groups, it would be difficult to effectively manage local network issues: as an analogy for understanding the importance of constraint groups, in digital communication, Routers and Switches (digital communication devices) are often deployed to segment one portion of the digital network from the other [56], further illustrated using Fig. C.1 in Appendix C.

Taking the constraint group 1 (depicted in Fig. 5 and Fig. 7) as an example of showing how constraint grouping aids deploying energy resources and managing variable renewables: the total constraint ('constraint' is used here to mean both constraint and curtailment through wind dispatch-down) in the NI electricity grid in 2018 was 250 GWh [35]. If 43% of the constraint occurs within the constraint group 1 as suggested in [36], then Table 1 gives a breakdown of the average constraint occurring within group 1 per day and per hour, the average maximum constraint occurring per day being under 720 MWh for 2018.

Table 1: Approximate Proportions of Wind Dispatch-Down in 2018

Months	**NI 2018 Total Volume (GWh)**	**Group 1 43% Volume (GWh)**	**Group 1 Constraint per Day (MWh)**	**Group 1 Constraint per Hour (MW)**
January	17.5	7.53	250.83	10.45
February	6.0	2.58	86.00	3.58
March	14.0	6.02	200.67	8.36
April	39.0	16.77	559.00	23.29
May	9.0	3.87	129.00	5.38
June	10.5	4.52	150.50	6.27
July	2.0	0.86	28.67	1.19
August	10.0	4.30	143.30	5.97
September	31.5	13.55	451.50	18.81
October	27.5	11.83	394.20	16.43
November	36.5	15.70	523.00	21.79
December	46.5	20.00	666.50	27.77

If there is an electricity arrangement that gives a priority dispatch to supplies from renewable sources and/or captured energy in line with the Single Electricity Market (SEM) Implementation of Regulation 2019/943 in relation to Dispatch and Redispatch [57], and if the average market trading interval (called the day-ahead market in NI electricity market) is 24 hours [41], then deploying a 720 MWh storage portfolio for group 1 could help prevent any constraints of the renewables within the group or any constraints occurring because of system needs (curtailments leading to constraints).

For more conservative deployment of resources, a smaller portfolio of storage could be deployed, say a 600 MWh portfolio for constraint group 1: while this portfolio may not eliminate all constraints, it could be more economical to deploy the smaller storage portfolio. Meanwhile, deploying a smaller storage portfolio could mean more demand for smarter controls necessary for using the smaller portfolio through multiple commitments to providing value services.

The increase in the share of variable renewable energy in the annual energy mix with the deployment of battery storage within the constraint groups is depicted in Fig. 8: as wind dispatch-down incidences increase through the years, the significance of the storage becomes increasingly evident.

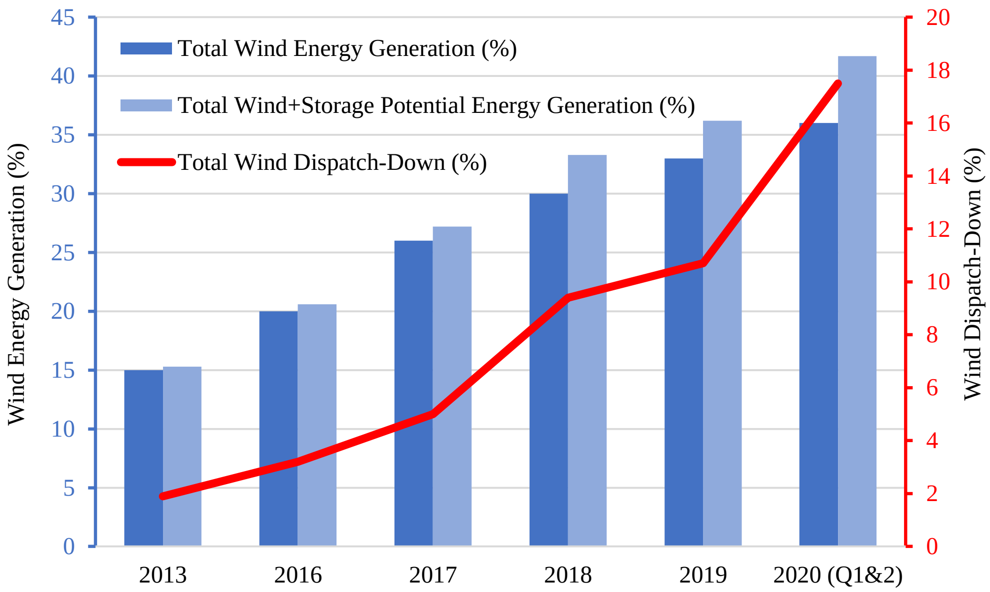


Fig. 8: Increased Share of Wind Energy Using Storage within Constraint Groups

The payback periods from using the storage portfolios through self-consumption energy, supplier energy, and for additional services are obtained. The payback periods are obtained by dividing the aggregated capital cost of the portfolios by the value of the service provided, taking the maintenance cost of storage as negligible.

To investigate how other value streams could impact the economics of the storage deployment, the values of the other services that the storage device could provide are estimated. With smart controls and as reported in [43], a storage device could be deployed for multiple services. The aggregated values with the associating payback periods are obtained. The results show that payback periods are far beyond the expected lifespan of the storage device when committing the device for one-function services. The results also suggest that, in deploying storage for managing constraints of variable renewables, other value streams will be required to make the deployment economical. The results show much lower payback periods with some cases having payback periods within the lifespan of the deployed lithium-ion battery. The results also indicate how storage cost could determine the economic feasibility of a storage project: as would be expected, the deployment becomes more profitable as the storage cost reduces: Table B.2 of Appendix B for a standard cost (£525/kWh) scenario and Table B.3 of Appendix B for a 50% lower cost (£263/kWh) scenario.

The payback periods are plotted in Fig. 9 for comparison: it could be observed that, being able to use the storage device for multiple miscellaneous services or not could define the economic success or failure of the storage deployment. As depicted in Fig. 9, while using the storage for four-function services, the payback period certainly falls within the expected lifespan of the storage device; for the three-function and the two-function services, there are significant chances of having a payback period that falls within the device expected lifespan; the chances become elusive in a single function storage application.

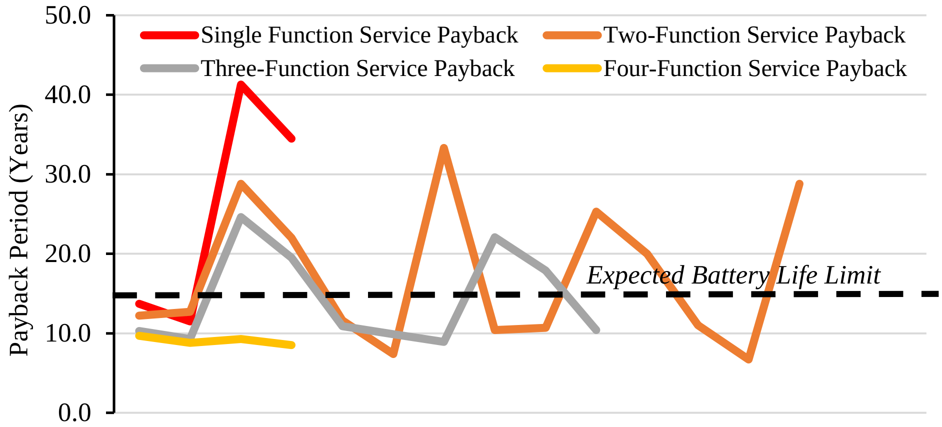
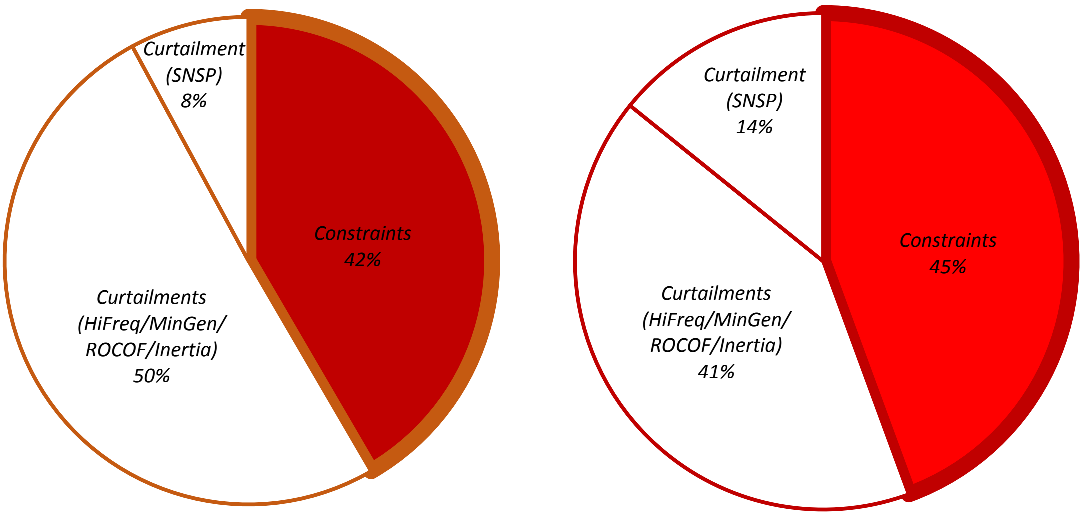


Fig. 9: Payback Periods at Single and Multiple Functions Battery Usage

For the results obtained, it is important to note that these are mass energy storage deployments, meaning that the market opportunities are taken as modest and equally available to individual storage units. While the payback for storage could take longer periods because of the levelized market stance typical of a competitive market, the deployment takes a system-wide perspective that makes increasing the share of variable renewables priority.

Meanwhile, some might argue that the money spent on acquiring the storage portfolios would be better spent on upgrading network infrastructure: but no level of infrastructural upgrade would eliminate curtailments arising from maintaining the required inertia and the SNSP levels; and upgrading selected portions of the network would not guarantee the removal of constraints at other network locations – hence, the value of load through storage. Moreover, storage provides a path to incremental infrastructure upgrades, deferring upgrades until they become, in fact, necessary – saving suboptimal or wasteful investments. In relation to SEM dispatch regulation in [57], solving curtailments with energy storage cancels the need for any current or future compensations paid for the curtailments that typically present additional cost burden to electricity consumers.

For a comparison between storage solution and conventional network upgrade solution: Fig. 10 depicts the categorisation of the wind dispatch-down in 2018 and in 2019, showing the typical proportion of constraints in the total annual wind dispatch-down [38]. Conventional network upgrade would resolve only about 42% of wind dispatch-down in 2018 and 45% in 2019 while storage could potentially resolve all forms of wind dispatch-down.



(a) 2018 Wind Dispatch-Down *(b) 2019 Wind Dispatch-Down*

Fig. 10: Categories and Percentages of Annual Wind Dispatch-Down in Northern Ireland in 2018 and 2019

Specifically, taking the 2018 data as a typical wind dispatch-down proportion and the definition for ‘constraint’ and ‘curtailment’ given in the NI electricity grid context: a conventional network upgrade through the installation of a new Kells-Rasharkin 110 kV Circuit within constraint group 1 will largely resolve constraints within the group [40]; additional equipment upgrades within the group (highlighted under Table 2) will resolve only about 42% (representing constraints) of dispatch-down.

Table 2: Planned Conventional Network Upgrade Solution Costs [58]

S/N	Upgrades and Uprates of Major Constraint-and-Renewables Integration Equipment within Constraint Group 1	Average Upgrade Cost (Million £)
1.	A New Creagh/Kells-Rasharkin 110 kV Circuit	23.60
2.	Coolkeeragh Reactive Compensation	21.00
3.	Coolkeeragh-Killymallaght-Strabane 110 kV Uprate	6.10
4.	Coolkeeragh-Trillick New 110 kV Circuit	9.80
5.	North West of NI 110 kV Reinforcement	32.00
6.	North West of NI Large-Scale Reinforcement	175.00
	Total	267.50

From the economic aspect, although the conventional solution would only resolve constraints, it is cheaper compared to the storage portfolios with battery cost over £150/kWh, Table 3; and the storage solution could only make economic sense where the storage device may be deployed for additional market services or when battery becomes extremely cheap, Fig. 9 and Table 3.

Table 3: Storage Portfolios Versus Conventional Network Upgrade Solution

Group-1 Wind Dispatch-Down Solutions	13-Year Solution Cost (Million £)	40-Year Solution Cost (Million £)	Management (Services)		
			Constraints	Curtailments (HiFreq/Min Gen)	Curtailments (SNSP)
One New Conventional Network Upgrade of Creagh/Kells-Rasharkin 110 kV Circuit [40,58]	23.60	23.60	√	–	–
Equipment Upgrade of Group 1 Major Constraint Elements [40,58]	267.50	267.50	√	–	–
Storage Portfolio 1 (720 MWh) at (£525/kWh)	378.10	1100.10	√	√	√
Storage Portfolio 2 (600 MWh) at (£525/kWh)	316.00	948.00	√	√	√
Storage Portfolio 1 (720 MWh) at (£263/kWh)	189.00	567.10	√	√	√
Storage Portfolio 2 (600 MWh) at (£263/kWh)	158.00	474.00	√	√	√
Storage Portfolio 1 (720 MWh) at (£120/kWh)	86.40	259.20	√	√	√
Storage Portfolio 2 (600 MWh) at (£120/kWh)	72.00	216.00	√	√	√
Storage Portfolio 1 (720 MWh) at (£12/kWh)	8.60	25.90	√	√	√
Storage Portfolio 2 (600 MWh) at (£12/kWh)	7.20	21.60	√	√	√

Meanwhile, as suggested in [59], one typical limitation of battery storage is its inability to continuously supply stored energy for “multi-day periods” because of capacity limitations; sizing the battery for multi-day continuous energy supply could not be economically feasible, except for dramatic battery cost reduction or technology breakthrough: in oversizing the battery, the extra capacity comes at extra cost and could become redundant within the limited lifespan of the device. Whereas other durable storage technologies that would not rely on the grid for discharging stored energy and with much longer lifespans than the battery could be more effective in handling multi-day storage of the excess variable renewable energy.

While working towards Net Zero, more energy must be produced from cleaner sources. In Northern Ireland, more energy generation from clean sources means more energy generation from variable renewables. More integration of the variable renewables into the electricity grid would mean more constraints and curtailments of the renewables: energy storage techniques would be required to capture and reuse the clean energy. While battery storage will not be the only energy storage solution, it has important role to play, and utilizing the battery storage for multi-function purposes makes storage economically feasible. The electricity system must be designed to accommodate equitable deployment of energy storage solutions to increase the use of energy from the available variable renewable energy resources.

In respect of the NI electricity grid, tools like WDT on the 110 kV network help to control the outputs of variable renewables; DS3 services and ISEM serve as additional revenue streams for storage. At the lower voltage levels of the electricity network, the DS3 services and the WDT could be extended; aggregation of loads, clustering of connections, standardised distributed resource management tools, and equitable tariff plans are essential.

The NI electricity grid is a small grid that could serve as microcosm of excellence in the integration of variable renewables. Other bigger grid stakeholders could take the NI grid as a test case in understanding how to effectively integrate higher proportions of variable renewables into the grid without the wastes arising from constraints and curtailments.

4. CONCLUSIONS AND POLICY IMPLICATIONS

Constraints and curtailments are a reality in power systems with high penetrations of variable renewables. While such restrains of clean energy resources are understandable in terms of maintaining the stability and reliability of the electricity grid, effective and optimal deployment of energy storage devices within constraint groups could help to prevent the restrictions on the variable renewable energy resources, leading to increased use of renewable energy resources necessary for achieving a more sustainable electricity system. The Northern Irish 110 kV electricity network presents an important test case for optimally deploying storage devices within constraint groups. In deploying the energy storage device within the constraint groups, the key findings are:

- **The constraint groups within the electricity grid segment the electrical system into group networks:** At such, energy storage devices could be localised to effectively manage the individual sub-networks and the variable renewable resources of the constraint groups within the grid.
- **There is a need for Wind Dispatch-Down (WDD) energy service:** The WDD energy service is to be in place such that any excess power flows that would be restrained are stored for later use. In Northern Ireland, if the devices deployed within the constraint groups at the 110 kV voltage level would be owned by individual storage investors, there should be an operator-defined service that the devices could commit to in taking up the excess clean power flows that would be restrained – like committing units through the DS3 market; the new service could be named: Wind Dispatch-Down – WDD.
- **The payback period on the investment on storage could go far beyond the lifespan of the storage device if there are no market arrangements that would permit the deployed storage device to derive additional value.** But with market opportunities such as energy arbitrage through ISEM, ancillary services through DS3 market, and energy use services, the deployed storage device could have payback period as short as seven years even where the market opportunities are modest.
- **Without a rewarding market arrangement, mass energy storage deployment would prevent the constraints and curtailments of variable renewables, albeit unprofitably, especially at higher storage costs:** In planning electricity grids, to remove the restrictions on the variable renewables and achieve a more sustainable energy system, it would be necessary to coordinate electricity resources such that optimal energy storage portfolios could be deployed for multiple services.
- **The system operator should regularly provide updates on the constrained area of the electricity network and liaise with the regulator to make available market arrangements for storage:** that would make it possible for storage devices to be deployed within constraint groups to manage wind

dispatch-down on the 110 kV network, participate in market opportunities through ISEM and DS3 market, and ultimately increase the share of renewable energy.

- **Upgrading network segments is still more economical than deploying battery storage until battery cost drops below £120/kWh;** however, while a conventional network upgrade would only remove constraints, storage helps to eliminate both constraints and curtailments of the variable renewables, provides a pathway towards incremental network investment, and having the storage deployed for providing multiple services could be rewarding.
- **Other forms of storage could be required to effectively eliminate Wind Dispatch-Down within the 110 kV Network:** For electricity grids with higher penetrations of variable renewables, other forms of storage – with more storage capabilities (seasonal storage and multiple-day storage) and lifespans than batteries' – could be required to fully eliminate the constraints and curtailments of gird-integrated variable renewables at the high-voltage supply side where customer devices cannot be directly connected.

Renewable resource conservation measures are especially important now that some fossil fuel-based power plants are scheduled for reduced capacity for sustainability and increase in power demand is expected from electrification of transport and heating even as we move towards achieving Net Zero. And hopefully, for the Northern Irish electricity grid and for similar wind-dispatch-down plagued grids, energy storage under equitable arrangements would eliminate wind dispatch-down such that as the share of renewable energy increases in the fuel mix, the Renewable Energy Constraint and Curtailment Reports would become Renewable Energy Storage Reports.

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APPENDIX A

Table A.1: Highlight of Key Parameters of Battery [43]

Make & Model	Tesla Powerpack 2.5
Battery Technology	Lithium Ion
Rated Power	1.11 MW
Storage Capacity	2.15 MWh (Approximately 2 hours at full power)
Depth of Discharge	100% of nameplate
Physical Space	44 m^2 (including clearance)
Total Weight	25.7 tonnes (excluding foundation)
Total Project Cost	$2.05 million ($954/kWh): in AUD$
Controller	Custom developed control for demand response
Average Round-trip Efficiency	*85.5%
Desirable Battery Features	Energy density, Capability to quickly swing between charging and discharging, Fast frequency response, Maturity of device technology
Warranted Lifespan	10 years
Expected Lifespan	15 years
Nominated Lifespan	**12.5 years

*The mean efficiency between the nameplate round-trip efficiency of the battery under normal conditions (86.5%) and the practical round-trip efficiency during a few hot Australian months of the year (84.5%) [43]. **The mean lifespan between the warranted lifespan and the expected lifespan of the battery.

Table A.2: Breakdown of the Capital Cost of Battery [43]

Expenses	**Cost (AUD$)**	**Cost (AUD$/kWh)**	***Cost (£)**	***Cost (£/kWh)**
Battery acquisition	1,700,000	791	935,000	435
Battery balance-of-plant and commissioning	182,000	84	100,100	46
Site preparation and construction	135,000	63	74,250	35

Software	35,000	16	19,250	9
Total	2,052,000	954	1,128,600	525

*Conversion rate at 1AUD$ = £0.55

APPENDIX B

Table B.1: Base Payment Rate of Storage-Eligible DS3 Services (October 2019 to September 2020)

Main Storage-Eligible Products	**Abbreviation**	***Payment Rate (€/MWh)** [60]	****Payment Rate (£/MWh)**
Fast Frequency Response	FFR	2.16	1.90
Primary Operating Reserve	POR	3.24	2.85
Secondary Operating Reserve	SOR	1.96	1.73
Tertiary Operating Reserve 1	TOR1	1.55	1.36
Tertiary Operating Reserve 2	TOR2	1.24	1.09
Replacement Reserve (Synchronised)	RRS	0.25	0.22
Replacement Reserve (De-Synchronised)	RRD	0.56	0.49
Fast Post Fault Active Power Recovery	FPFAPR	0.15	0.13
Ramping Margin 1	RM1	0.12	0.11
Ramping Margin 3	RM3	0.17	0.15
Ramping Margin 8	RM8	0.16	0.14
Total		11.56	10.17

*Conversion rate at £0.9166 = 1€; **Conversion rate at 1€ = £0.88

Table B.2: Payback Period of Storage Portfolios at Standard Cost (£525/kWh)

Application of Storage Portfolio in Miscellaneous Services: Storage Portfolio at Standard Cost (£525/kWh)	**Portfolio 1 Payback Period (Years)**	**Portfolio 2 Payback Period (Years)**
Self-consumption of Stored Energy Valued £0.15/kWh (SC) Only	27.4	22.9
Supplier Energy at Average Selling Price of £49.76/MWh (SE) Only	82.7	69.1
SC + [10% Capacity to DS3 Services in MWh per year for 12.5 years (CS1)]	24.5	20.8
SC + [10% Capacity to DS3 Services in Eight Non-Summer Months within 12.5 years (CS2)]	25.4	21.5
SE + [Energy Arbitrage Through ISEM in Summer Months within 12.5 years at £2.89/MWh Profit (EA1)]	57.5	50.6
SE + [Energy Arbitrage Through ISEM in Summer Months within 12.5 years at £5.78/MWh Profit (EA2)]	44.1	40.0
SE + [Opportunistic Energy Arbitrage Through ISEM within 12.5 years at £50.78/MWh Profit (EA3)]	23.2	22.0
SC + EA3	14.8	13.4
SE + CS2	66.7	57.6
SE + EA1 + EA3	20.7	19.7
SE + EA2 + EA3	18.6	17.9
SE + CS2 + EA1	49.3	44.2
SE + CS2 + EA2	39.1	35.8
SE + CS2 + EA3	21.7	20.7
SE + CS2 + EA1 + EA3	19.5	18.7
SE + CS2 + EA2 + EA3	17.7	17.0

Table B.3: Payback Period of Storage Portfolios at 50% Lower Cost (£263/kWh)

Application of Storage Portfolio in Miscellaneous Services: Storage Portfolio at 50% Lower Cost (£263/kWh)	**Portfolio 1 Payback Period (Years)**	**Portfolio 2 Payback Period (Years)**
Self-consumption of Stored Energy Valued £0.15/kWh (SC) Only	13.7	11.5
Supplier Energy at Average Selling Price of £49.76/MWh (SE) Only	41.3	34.5
SC + [10% Capacity to DS3 Services in MWh per year for 12.5 years (CS1)]	12.2	10.4

SC + [10% Capacity to DS3 Services in Eight Non-Summer Months within 12.5 years (CS2)]	12.7	10.7
SE + [Energy Arbitrage Through ISEM in Summer Months within 12.5 years at £2.89/MWh Profit (EA1)]	28.8	25.3
SE + [Energy Arbitrage Through ISEM in Summer Months within 12.5 years at £5.78/MWh Profit (EA2)]	22.0	20.0
SE + [Opportunistic Energy Arbitrage Through ISEM within 12.5 years at £50.78/MWh Profit (EA3)]	11.6	11.0
SC + EA3	7.4	6.7
SE + CS2	33.3	28.8
SE + EA1 + EA3	10.3	9.9
SE + EA2 + EA3	9.3	8.9
SE + CS2 + EA1	24.6	22.1
SE + CS2 + EA2	19.5	17.9
SE + CS2 + EA3	10.9	10.4
SE + CS2 + EA1 + EA3	9.7	9.3
SE + CS2 + EA2 + EA3	8.8	8.5

APPENDIX C

Understanding Constraint Groups Through Digital Communication: Routers keep a routing table that contains information about the properties and location of each digital sub-network (analogous to the local electricity network of each constraint group in power systems) within the global digital network (analogous to the aggregate electricity grid in power systems): through the information, the devices track data source and destination, breaking broadcast domains (analogous to constraint divisions in a power system), Fig. C.1. Switches do something similar with respect to breaking collision domains. Without the breaking of the collision and the broadcast domains, data communication would be almost impossible – data traffics (analogous to power flow in power systems) would move about the communication system perpetually until traffics within the system reach a standstill from network congestion. The functionality of the digital Routers and Switches are analogous to the works of the WDT and GDT. While the digital devices periodically update their information tables, the system operator, using the WDT, updates the changes to the composition of the constraint groups as the electricity network evolves.

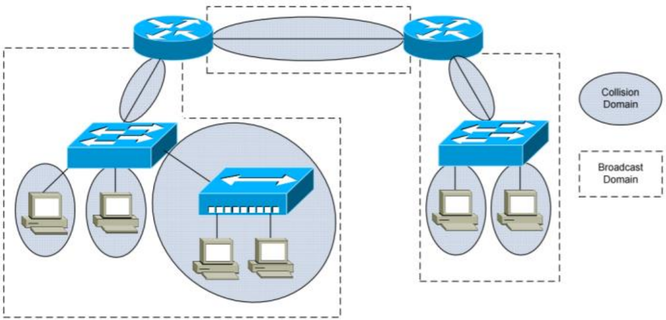

Fig. C.1: Digital Broadcast and Collision Domains Illustrating Electrical Network Constraint Grouping [56]

CRediT

Oluwasola O. Ademulegun: Conceptualization, Resources, Methodology, Formal analysis, Visualization, Writing - Original draft preparation. **Patrick Keatley:** Conceptualization, Resources, Writing - Review & Editing, Supervision. **Neil J. Hewitt:** Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition.

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