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Large-scale energy storage methods for wind energy

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This Briefing Paper explores potential options for the integration of wind energy and grid-scale energy storage systems into the energy infrastructure of Northern Ireland within the context of governmental net zero goals. It includes relevant international agreements, prevailing legislation in the wider United Kingdom, Northern Ireland specifically, and the Republic of Ireland. Subsequent sections offer a more technical explanation of the most relevant technologies, including key economic implications of each method.

1 Introduction

This Briefing Paper discusses wind power and the use of the most relevant grid scale energy storage methods in the context of governmental net zero goals relating to decarbonisation in Northern Ireland the wider United Kingdom, and the Republic of Ireland.

The Paper provides context-setting information about relevant international agreements in this area, which underpin prevailing legislation aimed at reaching zero goals in the wider United Kingdom, Northern Ireland specifically and in the Republic of Ireland, along with their related government strategies and schemes. Following on, the Paper explains the technical details of wind power and energy storage - featuring existing or planned examples, where possible. The Paper aims to increase knowledge, understanding and awareness of the scientific concepts which prevailing law and related government strategies and schemes seek to harness and regulate. Thereafter, the Paper makes some concluding remarks, in view of the evidence examined.

The Paper is presented as follows:

1. Introduction
2. Context-setting – decarbonisation
3. United Kingdom and Republic of Ireland legislation, strategies and schemes
4. Wind power
5. Energy storage
6. Concluding remarks

Note: this Briefing Paper draws upon policy documents published under the previous United Kingdom Government. At the time of writing, it is unclear as to what direction the current Government will adopt with regard to energy storage.

This Briefing Paper is not intended to address the specific circumstances of any particular individual. It should not be relied upon as professional legal advice or as a substitute for it.

2 Context-setting – decarbonisation

In the past three decades, governments around the world have set out to move away from fossil fuels and increasingly adopt low carbon electricity generation methods and industrial processes. This is generally known as “decarbonisation”. Key relevant developments in this area include the establishment of the 1988 Intergovernmental Panel on Climate Change, which published its first report about climate change in 1990[1]. The report provided the basis for setting up the United Nations Framework Convention on Climate Change (UNFCC), which facilitated the drafting and signing of landmark agreements that aim to define ways in which decarbonisation can be done.

The first of the most important international agreements facilitated by the United Nations is the 1997 Kyoto Protocol, which committed signatories to drastic reductions in greenhouse gas emissions. Then came the 2015 Paris Climate Accords, which set a goal to keep the global average temperature increase to well under 2 °C compared to pre-industrial levels, by roughly halving carbon emissions by 2030 and reaching net zero emissions by 2050[2].

Decarbonisation depends on low carbon energy generation, provided by solar, geothermal, hydro, wind and nuclear power sources to mention only the most important ones. Among these, nuclear is capable of a constant output, but is non-renewable, while the others all are renewable, but intermittent. This Paper concentrates on wind power, as it is the most relevant low-carbon, renewable energy source for Northern Ireland. It first discusses the legislative environment surrounding renewable energy generation methods in the whole of the United Kingdom, in Northern Ireland specifically and in the Republic of Ireland. Then a more technical discussion of wind energy is given, along with relevant energy storage technologies.

[1] All IPCC reports can be found here.

[2] Net zero in this context means that any emission of carbon is balanced by the same amount of carbon being removed from the atmosphere.

3 United Kingdom and Republic of Ireland legislation, strategies and schemes

Within the wider context of climate change policy, countries such as the United Kingdom and the Republic of Ireland have used legislation to drive decarbonisation, including, among other things, renewable electricity generation support schemes to incentivise development. This section outlines legislation, energy strategies and subsidy schemes – both existing and under development – in the whole of the United Kingdom, Northern Ireland specifically, and the Republic of Ireland.

3.1 Legislation and strategies

In Section 2, the Paper highlighted international agreements that are relevant in this area; the United Kingdom, including Northern Ireland, and the Republic of Ireland are signatories of those agreements. To transpose and implement the agreements into the law of those three jurisdictions, the following legislation has been enacted since:

- United Kingdom-wide: Climate Change Act in 2008
- Northern Ireland-specific: Climate Change Act (Northern Ireland) 2022
- Republic of Ireland - Climate Action and Low Carbon Development (Amendment) Act 2021; also in line with the European Union (EU) Climate Law and the EU Green Deal

These pieces of legislation set out how these jurisdictions aim to reach net zero emissions by 2050 as set out in the international agreements. Each named act requires emissions of greenhouse gases to be drastically reduced and the remaining emissions to be balanced by greenhouse gas removal from the atmosphere.

In practice, the aims of these acts are to be delivered through actions specified in net zero strategies. The United Kingdom's Net Zero Strategy published in 2021 aims to fully decarbonise power generation in Great Britain, including the adoption of 40 gigawatt (GW) of off-shore wind capacity (for reference, as of 2023 the United Kingdom has about 15 GW onshore and 15 GW off-shore wind capacity). That was increased to 50 GW by a 2023 Department for Energy Security and Net Zero policy paper. The United Kingdom has also set out an ambition of developing 5 GW of low-carbon hydrogen production capacity by 2030. The Northern Ireland Department for the Economy's 2021 Energy Strategy sets out the aim of meeting at least 70% of Northern Ireland's electricity demand from renewable sources by 2030. This target was increased to 80% by the Climate Change Act (Northern Ireland) 2022. As part of their national net zero initiatives, the governments of both the United Kingdom and the Republic of Ireland have published their strategies on how hydrogen will be included in their industrial strategies.

The Republic of Ireland aims to achieve net zero greenhouse gas emissions by 2050; this is reflected by the 2019 Climate Action Plan. This involves ending the usage of coal and peat for power generation, and increasing reliance on renewable electricity generation from 30% to 70% by 2030, including the adoption of up to 8.2 GW onshore wind capacity. In addition to this, the Climate Action and Low Carbon Development (Amendment) Act 2021 commits to a 51% reduction in greenhouse gas emissions by 2030 compared to 2018. Energy generation, and heavy industries in the Republic of Ireland make up a smaller part of overall emissions than the European Union average, whereas agriculture, transport and the maintenance of buildings collectively make up the majority of emissions. Because of this, the net zero strategy of the Republic of Ireland relies more on energy efficiency increases and low carbon land use than building renewable energy generation infrastructure.

3.2 Renewable support schemes in the United Kingdom and the Republic of Ireland

Both the United Kingdom and the Republic of Ireland provide subsidy schemes for eligible producers of renewable electricity. The terms of eligibility and the overall details of these schemes are discussed in the following sections.

Great Britain-specific Renewable Obligation schemes

In Great Britain, subsidising renewable electricity production happened through the Renewables Obligation (RO) scheme in England and Wales, and through the Renewables Obligation Scotland (ROS) scheme in Scotland up until 2017. Both the RO and ROS schemes closed to new generating capacity in 2017, which means that no new applications are accepted, but the subsidies already awarded will run their course until 2037 at the latest.

Both the RO and ROS schemes required electricity suppliers to present a certain number of RO Certificates (ROCs) to the Office of Gas and Electricity Markets (Ofgem). ROCs could either be obtained by producing renewable electricity or by buying certificates from other companies which do.

The United Kingdom's Government, and the Scottish Government are considering introducing a Fixed Price Certificate (FPC) model into the RO and ROS scheme for the remainder of their funded periods. There was a period of evidence gathering for this decision that ended in October 2023.

Great Britain-specific Contracts for Difference scheme

Since the end of the RO scheme in 2017, the United Kingdom's Government has subsidised renewable energy in England and Wales though a Contracts for Difference (CfD) scheme. This is jointly carried out by the Whitehall Department for Energy Security and Net Zero, National Grid Electricity System Operator, Low Carbon Contracts Company and Ofgem. The scheme is made up of a series of auctions, where eligible low carbon electricity suppliers in Great Britain can bid for funding from one of two pots of money.

The first funding pot is for established technologies like onshore wind, solar photovoltaics, or hydropower among others. The second funding pot is for less established technologies like offshore wind, wave and tidal power, or anaerobic digestion. The lower capacity limit for proposed projects is generally 5 megawatt (MW), or 50 MW in the case of hydro power, which means CfD funding is aimed at relatively large projects. "Auctions", also known as "allocation rounds", are held every year or so, for a certain amount of funding in pot 1, pot 2 or both.

Successful applicants of allocation rounds are paid a flat rate for the low carbon electricity they produce for 15 years. The rate is equal to the difference between the average market price for electricity in Great Britain, also called "reference price", and what is called a "strike price". When the market price for electricity is lower than the strike price, the generator receives a payment to bring revenue up to the strike price. When the market price for electricity is above the strike price, the generator pays back the difference between the two. Thus, the scheme practically encourages investment in low carbon electricity production, without significant price increases to customers.

United Kingdom-wide Smart Export Guarantee scheme

The Government of the United Kingdom also launched the Smart Export Guarantee (SEG) in 2020, which subsidises smaller renewable projects. This scheme is taking over after the expiry of the previous Feed in tariff (FiT) scheme. The eligible maximum capacity for SEG funding is 5 MW for most technologies, and 50 kilowatt (kW) for combined heat and power sites, serving individual homes or small businesses. Along with the CfD scheme, SEG are only available for developments in Great Britain.

Republic of Ireland-wide Renewable Electricity Support Scheme

The corresponding scheme in the Republic of Ireland is the Renewable Electricity Support Scheme (RESS), which was designed in line with the European Union’s Clean Energy Package, carrying out the aims of the European Green Deal. It provides financial support for onshore wind, solar, hydro, and some biomass, biogas, and waste heat harvesting electricity projects of capacities above 0.5 MW. The RESS is also a CfD scheme. The successful applicants of allocation rounds are entitled to a support payment when energy generated by their plant is more expensive than the average market price, but are also liable to pay a difference payment when the opposite is true.

Republic of Ireland-wide Micro-generation Support Scheme

The Republic of Ireland also operates a separate scheme for small capacity electricity generation called Micro-generation Support Scheme (MSS). The MSS supports domestic solar photovoltaics applicants with capital grants, or non-domestic applicants like schools and community buildings of any eligible installations of up to 6 kilowatt-hour (kWh) capacity.

Northern Ireland-specific Renewable Electricity Support Scheme

Northern Ireland operated a scheme similar to the United Kingdom's RO, called Northern Ireland Renewables Obligation (NIRO) scheme. The NIRO, along with RO and ROS schemes in Great Britain, closed for new applications in 2017. The Northern Ireland Executive is considering introducing a Fixed Price Certificate (FPC) model into the NIRO scheme for the remainder of its funded periods; this is in parallel with considerations about introducing FPC into the Great Britain-specific RO and the Scotland-specific ROS. There was a period of evidence gathering for this decision that ended in October 2023.

A new scheme has since been announced by the Northern Ireland Department for the Economy (DfE), called Renewable Electricity Support Scheme (RESS), which ends the period since 2017 with no renewables subsidy program.

The RESS aims to deliver Northern Ireland's aim of producing at least 80% of its electricity from renewable sources in accordance with the Climate Change Act (Northern Ireland) 2022. Following a report commissioned by the DfE and internal research, it was decided that the most appropriate scheme for Northern Ireland would be a CfD scheme[3]. It was also decided that due to Northern Ireland's physical location, it is not appropriate to seek integration into the CfD scheme operated in Great Britain. Instead, a bespoke scheme is necessary, which is currently under development. The development of this scheme also relies on a Cornwall Insight report.

The DfE concluded its public consultation on the upcoming RESS in April 2023. According to a report by Aurora Energy Research, the scheme's first auction could take place in 2025, with delivery of projects potentially starting around 2027. Aurora Energy Research was involved in the development of this scheme on the DfE's behalf.

Potential Northern Ireland-specific microgeneration support scheme

It is worth mentioning that the NIRO also provided support for microgeneration up until 2017. The main eligibility criteria were that electricity must be generated

[3] A. Foley et al. (2021). *Support scheme options to incentivise renewables investment in Northern Ireland: Report for the Department for the Economy as evidence for the Northern Ireland Energy Strategy 2021*. Queen's University Belfast.

from solar photovoltaics, wind or hydropower, and that the declared net capacity of the station must be below 50 kW. The specifics of this microgeneration support scheme give an indication of what could be expected from a potential new scheme.

Potential pros and cons are under consideration for a separate microgeneration support scheme. Northern Ireland's DfE has stated that the main argument for a microgeneration scheme is that it could form part of a just transition where lower income households could receive support in the form of funding towards some form of renewable microgeneration. The DfE has also noted that the main argument against a microgeneration support scheme is its limited potential regional impact. Based on the outcomes of past microgeneration scheme allocation rounds in Great Britain, residential renewables contribute very little to regional renewable goals.

4 Wind power

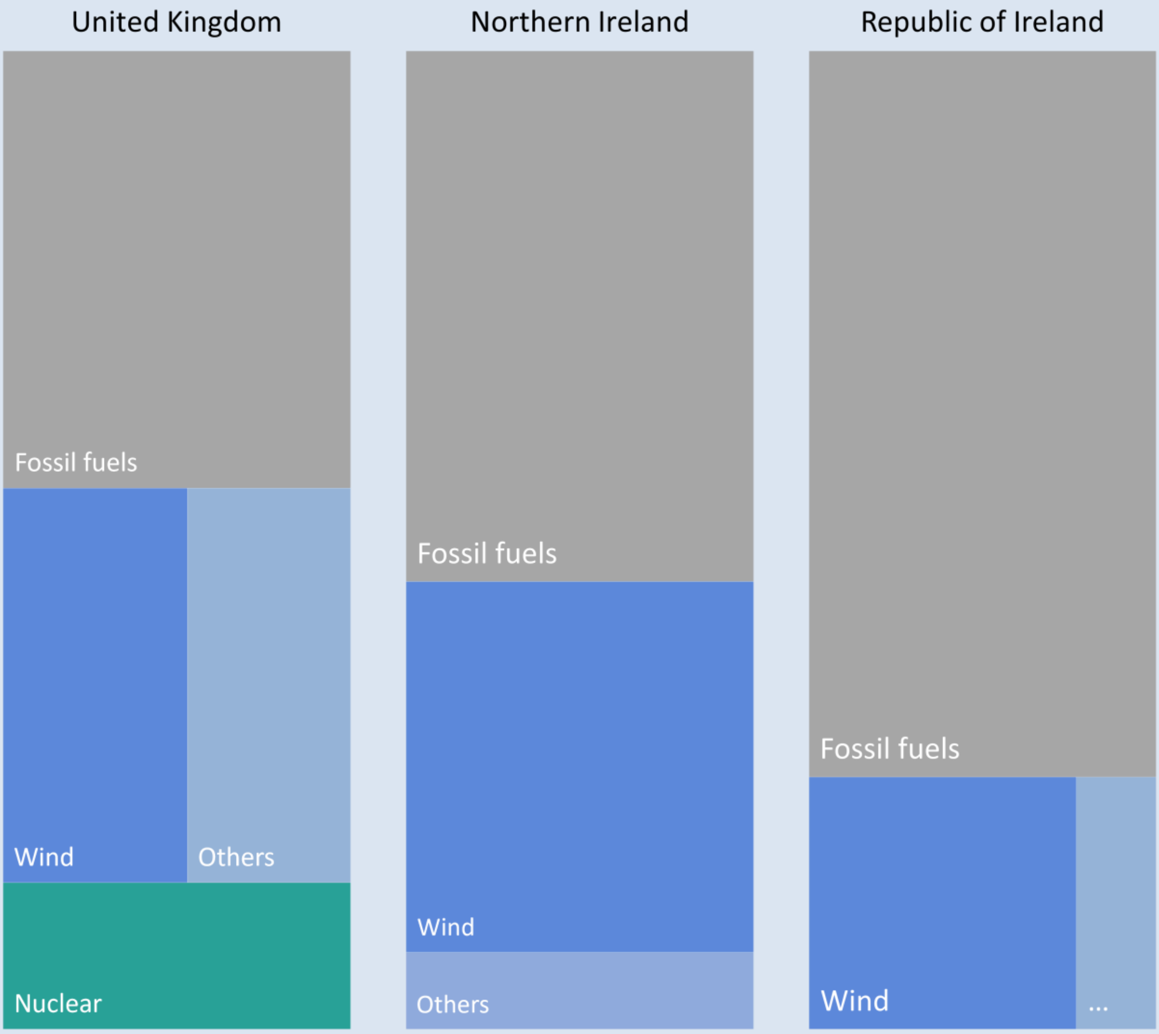
Following the legislative background of renewables in sections 1 to 3, this section now seeks to explain the technical details of wind power and energy storage. It seeks to increase knowledge, understanding and awareness of the scientific context which the law and its strategies and schemes aim to harness and apply.

The term "wind power" is used to describe the transformation of the kinetic energy in winds into mechanical work, like turning a turbine and thus generating electricity. Wind power is one of the cheapest, cleanest renewable energy sources and the most abundant renewable power resource in the United Kingdom and the Republic of Ireland. Accordingly, wind already plays a large part in generating the electricity used across the United Kingdom and the Republic of Ireland (see Box 1 below).

According to a 2020 International Energy Agency report, the median levelised cost of electricity generation for onshore wind was 50 dollars (United States) per megawatt-hour power generated (USD/MWh). The only cheaper source was nuclear at 32 USD/MWh. Moreover, a 2020 European Topic Centre on Climate Change Mitigation report identified onshore wind, nuclear and hydropower as the cleanest energy sources at roughly 13 kg CO_2 equivalent emissions per megawatt-hour (MWh) generated power.

However, most types of renewables generate energy intermittently, which can be more or less predictable, and thus their large-scale utilisation requires grid-scale energy storage. For example, solar energy can be predictable to the extent that its generation always reaches its maximum when the sun is highest in the sky. On the other hand, wind energy does not follow a similar daily pattern, and instead varies from hour to hour, day to day. Solar energy is therefore intermittent, but predictable, so it can be reliably used to satisfy user demand without energy storage. Whereas wind presents greater challenges for its users, making storage of surplus energy production crucial if its potential use is to be maximised in terms of efficiency and effectiveness.

Box 1: Overview of electricity generation modes in the whole of the United Kingdom, Northern Ireland specifically and the Republic of Ireland



In 2023, 39.6% of total electricity demand was fulfilled using renewable sources in the whole of the United Kingdom. In the same year, 21.0% of consumption was from wind, while 18.6% was a combination of other types of renewables.

Department for Energy Security and Net Zero 2023

In 2023, 45.8% of total electricity demand was satisfied from renewable sources in Northern Ireland. In the same year, 38.0% of consumption came from wind power, while 7.8% came from various other renewables.

Department of the Economy 2024

In 2022, 40.7% of overall electricity consumption in the Republic of Ireland was provided by renewables, biofuels and biomass in 2022. In the same year, 20.7% of consumption was from wind, the rest various types of bioenergy.

Sustainable Energy Authority in Ireland 2023

A more detailed, interactive version of these graphs can be found here: United Kingdom; Northern Ireland; and, Republic of Ireland.

Source: RaISe 2024, relying on noted departmental and governmental sources noted in the Box.

Wind energy generation in Northern Ireland

Northern Ireland is one of the windiest regions of Europe. Average wind speeds are reliably high, but on a daily or hourly basis, wind is unpredictable and does not follow any trend.

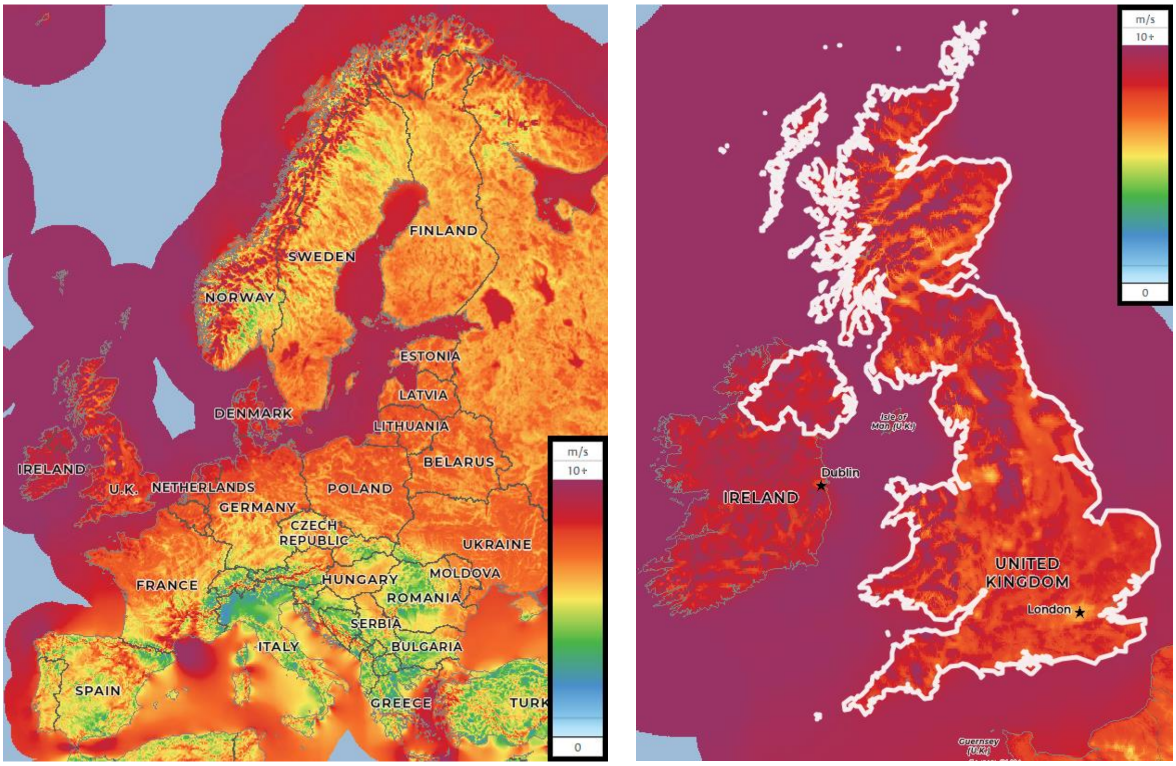
Figure 1 below illustrates the long-term average wind speeds being well above the minimum of about 4 m/s required for power generation. This makes wind a great candidate in fulfilling increasing Northern Ireland user demand for clean and sustainable energy.

However, as noted earlier, wind is variable and unpredictable. The wind speeds measured at the Lough Fea weather station, between January and March 2024 show that the average is roughly the same regardless of time of day, but this masks significant variances: it is equally likely that wind speeds are 2-3 or 14-15 m/s. Conversely, power demand follows a well-defined daily pattern (see left side of Figure 2)[4].

Large-scale electricity production from wind turbines without energy storage could lead to reliability issues due to the unpredictability of wind energy generation. Such an issue is expected to arise during large portions of the day when wind speeds are low, but energy demand is high. Because of this, there is significant interest in coupling the increasing adoption of wind power to large scale energy storage methods. This would effectively decouple the harvesting of wind energy from its use: energy harvested at any time of the day could be stored and then used at times of high energy demand. This strategy is often referred to as “load shifting” or “peak shifting”.

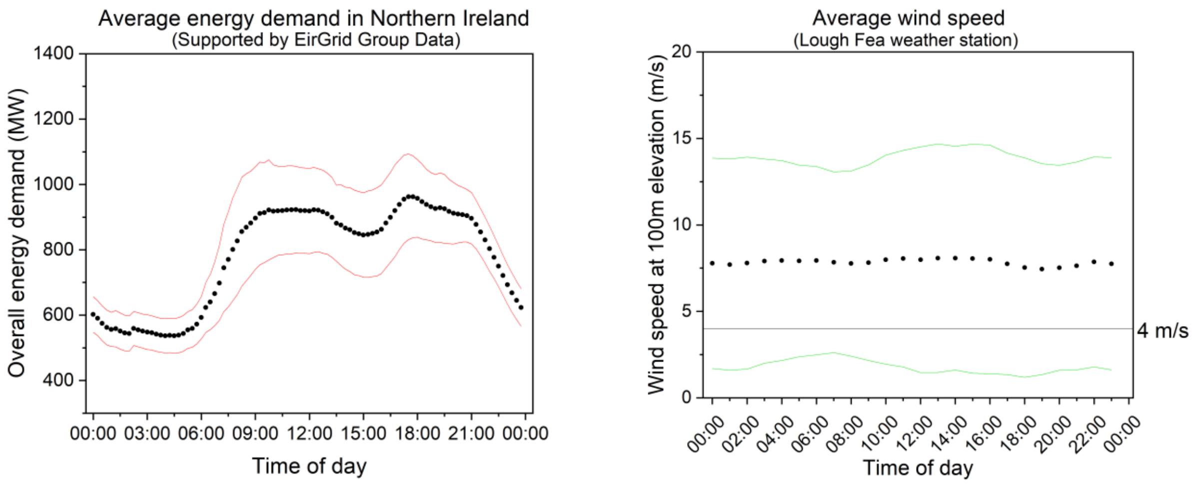
[4] Lough Fea was chosen as it showcases a near best case scenario for onshore wind due to its high altitude and central location in Northern Ireland.

Figure 1 - Long-term average wind speeds at 100 metres elevation in European Union countries and the United Kingdom and the Republic of Ireland, respectively



Source: [Global Wind Atlas](), 2023

Figure 2 – Graphs showing average energy demand vs time of day for Northern Ireland and average wind speeds vs time of day for the Lough Fea weather station



Sources: www.smartgriddashboard.com, 2024; www.weatheronline.com, 2024.

Perhaps the most important new wind energy project that has been announced for Northern Ireland is North Channel Wind, which is being developed by SBM Offshore and NMK Renewables Limited. This project forms part of the DFE's

Offshore Renewable Energy Action Plan. North Channel Wind aims to deliver a floating off-shore wind farm of more than 1 GW in overall capacity. The project is at the site characterisation and optimisation stage as of June 2024, construction is set to start in 2029 or 2030. North Channel Wind is made up of 2 proposed wind farms: North Channel 1; and, North Channel 2. The former has a proposed capacity of 1 GW, while the latter 420 MW. The sites of the wind farms are to be situated close to both the Moyle interconnector and the Ballylumford and Kilroot 400 kV transformation stations.

The DfE conducted a public consultation in December 2022, and a Statement of Intent was published in January 2023, in conjunction with The Crown Estate regarding leasing of the seabed. First power generation is planned for 2030, at the earliest.

The next section explores the most relevant large scale energy storage methods that can be combined with an intermittent energy source, such as wind in the case of Northern Ireland.

5 Energy storage

This section explores the most relevant, currently available energy storage methods, which can be combined with an intermittent energy source such as wind in the case of Northern Ireland.

First, it is necessary to explain "grid scale energy storage", which was a very small part of the global energy economy up until the 2010s. Widescale use of fossil fuels and nuclear power plants made energy storage unnecessary, as they provided a constant base load. As a consequence, grid-scale energy storage has not been implemented in any country to any significant extent. With the current rapid upward trend in adopting intermittent renewable energy sources, as highlighted in section 2 and 3 of this Paper, there is increasing interest in developing and implementing energy storage methods, in order to maximise the efficiency and effectiveness of these renewables.

Within that context, this section provides an overview of the most common energy storage methods – mechanical and chemical – that are relevant to the

United Kingdom and the Republic of Ireland, including existing or planned examples, where possible.

5.1 Mechanical energy storage

The simplest grid scale energy storage methods use some kind of mechanical process to store the intermittent energy of renewables, like pumped hydro or compressed air energy storage. These methods tend to be capital intensive, have long lead times, and can only be used on a grid scale, not on household or municipal scales. Nonetheless, they also provide energy storage with low operational costs and a decades' long operational life[5]. Typical capacities are in the range of 10 to several thousand MW[6].

Pumped hydro energy storage (PHES) works by using surplus energy from renewables to pump water from a lower reservoir to a higher one when overall energy demand is low. The water can then flow back down through turbines and generate electricity when energy demand is higher. To enable PHES, the local geology should mainly be made up of hard rock, in order to allow for the construction of robust underground halls and tunnels. In the case of the United Kingdom, this means that the best candidates for PHES sites are in the Scottish Highlands and Snowdonia. There are four operational PHES stations in the United Kingdom: Dinorwig, Wales, Foyers, Scotland, Ffestiniog, Wales, and Loch na Cathrach, Scotland. There is one operational PHES station in the Republic of Ireland, at Turlough Hill, County Wicklow. There are no operational PHES sites in Northern Ireland. One site was in development near Camlough, County Armagh, but was later abandoned, some 50 years ago.

The other relevant mechanical energy storage method is the use of surplus energy from renewables, to compress air; often to the point of liquefying it. The high-pressure air can then be used to drive turbines to generate electricity. In

[5] N. McIlwaine et al. A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems.; *Energy* 229 (2021)

[6] B. Zakeri e al. Electrical energy storage systems: A comparative life cycle cost analysis; *Renewable and Sustainable Energy Reviews* 42 (2015) 569–596

such compressed air energy storage (CAES), air is pumped into large metal vessels, airtight underground caverns or underwater pressure tanks.

Airtight underground caverns are often created by removing most of the salt from underground salt deposits. The first step toward using such caverns as any type of gas storage is to hollow out the salt deposits by partially dissolving it, and pumping the resulting brine into the ocean at an offshore site that does not endanger coastal wildlife. Large masses of porous rock can also be used as the gas storage medium.

This is quite relevant for Northern Ireland because the coast of Belfast Lough and the wider Lagan Valley are rich in deep salt deposits[7], and there are areas with hard or porous rock there as well[8].

Moreover, there are deep salt deposits under Larne Lough in County Antrim, which have been deemed suitable for gas storage and because of this there has been a lot of interest in development. Among others a CAES site by Gaelectric was in development in the area between 2008 and 2018. The company had planned to build a 330 MW capacity energy storage plant, and some progress was made, but the project was later discontinued before construction began due to Gaelectric failing to acquire investment and ultimately going out of business.

More recently, Islandmagee Energy, a company owned by Harland and Wolff, announced plans to develop a natural gas storage site under Larne Lough. This project has since been challenged on environmental and legal grounds, as highlighted below.

An environmental campaign group, won a legal bid against Islandmagee Energy, claiming the marine construction license was given in error. That means, at present, it is uncertain if construction can ever begin on this project.

[7] H. Blanco et al. A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage. *Renewable and Sustainable Energy Reviews* 81 (2018) 1049–1086, Appendix C

[8] A. Aghahosseini et al. Assessment of geological resource potential for compressed air energy storage in global electricity supply. *Energy Conversion and Management* 169 (2018) 161–173

Moreover, the above development could affect the chances of other energy storage sites aiming to use such caverns in Northern Ireland, as the salt would have to be dissolved at those other sites, and thus the potential environmental concern about the resulting brine remains.

In this context, it also is worth noting Greater Manchester's CAES site, which proposes to use liquid air as the energy storage medium. It is in the early stages of planning, the developer, Highview Power, is currently in the process of raising funds.

5.2 Chemical energy storage

"Chemical energy storage" is a broad term for a number of energy storage methods where electricity is used to bring about a lasting chemical change, like producing a molecule. Strictly speaking, chemical energy storage is used to mean the production of hydrogen, but other molecules can be produced through a subsequent process, like ammonia, methane or methanol. All of these materials can be used as either fuels or industrial resources. Storing energy in batteries also falls under the umbrella of chemical energy storage (Please note that the depth of this topic warrants separate discussion in sub-sections 5.3. and 5.4.). Finally, sub-section 5.5. mentions some key emerging technologies in battery energy storage.

Hydrogen

Hydrogen is a very important resource and energy carrier of global heavy industries. Its most important uses are the purification of metals, the synthesis of ammonia and by extension ammonium nitrate fertilisers. It can also be coupled to carbon capture, which would lead to the production of methane or methanol from carbon monoxide (CO) or carbon dioxide (CO_2).

Hydrogen can be injected into already existing gas pipelines to increase energy density or it can be used as a fuel either in a combustion engine of a fuel cell. Its storage and transport require high purity stainless steel vessels or pipes. Alternatively, it can be stored in underground caverns where local geology allows. There are many experimental chemical storage methods as well, but none of these are ready for industrial usage.

While there is naturally occurring hydrogen gas deep within the Earth's crust, its extraction is not viable today, which means practically all hydrogen used is industrially produced. The main ways of producing hydrogen are:

- steam reforming of natural gas with or without coupled carbon capture (grey or blue hydrogen respectively)
- through water electrolysis (green hydrogen).

Blue and green hydrogen are also grouped together as low carbon hydrogen. The production of green hydrogen is also a promising energy storage method as the intermittent energy from renewables could be used to generate hydrogen in an environmentally friendly way. It should also be noted that the electrolysis of water produces both hydrogen and oxygen, so for maximum efficiency the generated oxygen should be used in some way, as well.

As a fuel, hydrogen produces only water vapour as exhaust. It compares to natural gas favourably in some sense, but not others. Its specific energy[9] is more than double that of natural gas, but its energy density[10] is only about a third of it. This makes hydrogen an attractive clean fuel in applications where the size of the storage vessel is not a crucial factor - for example, stationary energy storage or heavy-duty vehicles like buses and ships. It also limits its potential use in light vehicles, as large tanks would negatively affect fuel economy.

It should be noted that hydrogen based internal combustion engines are rare, most existing examples are experimental designs, like the Kawasaki Ninja H2R, or only prototyopes yet, like the Toyota Corolla Cross Hydrogen Concept. There are also hydrogen combustion engines in development for industrial use, like JCB's hydrogen combustion engine. Most hydrogen powered vehicles use fuel

[9] Specific energy is the amount of energy a material holds per unit of mass, most commonly expressed in megajoule per kilogram (MJ/kg) for fuels.

[10] Energy density is defined as the amount of energy held by a material per unit of volume, typically expressed in megajoule per cubic metre (MJ/m^3).

cells where hydrogen reacts with the oxygen content of air to produce an electric current. Both hydrogen internal combustion engines and fuel cells require hydrogen to be stored in tanks on board the vehicle.

Despite the promising nature of hydrogen, opinions around a potential hydrogen economy are strongly divided. The drawbacks most often mentioned are the high costs, low efficiency and small number of potential applications. The upfront costs of water electrolysers are much higher than was expected by this time. The near-term estimate for green hydrogen is about 4-6 US dollars per kg (USD/kg); experts forecast a price of about 3 USD/kg for the near future. That translates to a cost of about 90-200 USD/MWh, depending on efficiency of power generation. For comparison, natural gas costs 35 USD/MWh[11].

The main reasons why green hydrogen is so expensive is that electrolysers turn only a relatively small amount of electricity into hydrogen, and some of the components needed to construct electrolysers are very expensive (for example platinum, iridium). The most common types of electrolysers are proton exchange membrane and alkali electrolysers. The former has a typical efficiency of 60%; while the latter 63-73%[12].

There has been a lot of interest in a hydrogen economy in the past decades, and a key take-away is that the areas in which hydrogen can be economically used is much narrower than previously thought. Nevertheless, green hydrogen remains the ideal solution for decarbonising steelmaking, long distance aviation, and international shipping to name a few.

There are a number of initiatives in Northern Ireland and the wider United Kingdom connected to hydrogen in various stages of development. For example, a planned hydrogen generation and storage facility near Glasgow aims to use the energy generated by the UK's largest onshore wind farm to produce hydrogen by water electrolysis. Northern Ireland Water plans to build a 1 MW electrolyser, which would produce hydrogen to be used as a fuel and

[11] Price representative of 20 June 2024.

[12] M. Yue et al. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews* 146 (2021), 111-180

oxygen to be used in water treatment. Translink has introduced over 100 zero emissions buses to its fleet, with 23 of these being hydrogen fuel cell electric vehicles. There is also a large proposed development for the Kilroot power station. The owner, EPUK Investments Ltd, aims to transform Northern Ireland's largest energy provider that has been coal fired up until recently, into an energy park including a solar farm, and a water electrolyser that will produce hydrogen. The power plant itself is expected to use natural gas to generate electricity. Other initiatives worth mentioning are the proposed Trafford Low Carbon Energy Park, which will include green hydrogen production, battery energy storage, the CAES site mentioned in sub-section 5.1, and a hydrogen hub in North West England.

5.3 Stationary battery energy storage

The global demand for battery energy storage systems is growing rapidly, stemming both from the electrification of transport and the movement towards increasing incorporation of renewables into national grids.

While the technological background of grid scale battery energy storage and EV batteries is generally the same, there are large enough differences between the practicalities of the two, to necessitate their separate discussion in sub-sections 5.3 and 5.4.

Grid scale battery energy storage

Storing energy in industrial capacity battery farms can be achieved by charging these batteries using only surplus energy from intermittent renewables. This enables storing energy at times of high renewable energy production, but low overall energy demand, and then using it at times of high overall energy demand.

The most important established battery chemistries are lead-acid and lithium ion batteries, as outlined in the below sub-sections, but some relevant emerging technologies will also be mentioned, like sodium ion batteries and vanadium redox flow batteries.

Lead acid batteries

A battery's chemistry defines technical parameters, like energy and power output, maximum capacity, maximum number of charge-discharge cycles, and durability and safety. By extension battery chemistry also defines economic parameters like costs and reliability of production and cost of operation.

Lead-acid batteries constitute a simple, relatively cheap and well-established energy storage method. Their robust battery chemistry allows for long-term energy storage with self-discharge rates[13] comparable to lithium ion batteries but they also tend to have much lower energy densities on both volume and mass bases than most other established battery types. This means that for any given capacity, lead-acid batteries will usually be larger and heavier than other battery types. This is a concern for EVs since size and weight affects car design and fuel economy, but is generally not a problem in grid scale energy storage as the batteries are stationary. A significant advantage of lead-acid batteries over other battery types is that raw materials are abundant and recycling is already possible at scale and in an economic way. Lead is a fairly common element, with an estimated total of 88 million tons of reserves, which can be extracted economically[14]. The inherent disadvantage of lead-acid batteries stems from the toxicity and environmental harm lead can cause, so the usage of these batteries must be paired with strict environmental and health regulations and enforcement of recycling[15].

Lithium ion batteries

Lithium ion batteries (LIBs) are one of the most common battery types that have become widely used in almost all areas of life. LIBs offer the highest energy density both in terms of volume and mass, for any rechargeable battery type, but are also relatively expensive and the raw materials necessary for their production come with some significant drawbacks. The most common LIBs are made up of 18650 cells (meaning 18 mm in diameter and 65 mm in length) containing an NMC cathode (nickel, manganese, cobalt).

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[13] Batteries gradually lose charge over time even if they are not in use. This is called self discharge.

[14] About 35 million tons of lead reserves are in Australia and another 17 million tons are in China.

[15] P.P. Lopez et al. Past, present, and future of lead–acid batteries. *Science* 369/6506 (2020), 923-924

More than half of high purity nickel imported by the EU and United Kingdom comes from Russia. Imports of nickel from Russia have been banned following the Russian invasion of Ukraine. This has introduced a measure of uncertainty into supply chains. Cobalt mining also poses significant supply chain and ethical problems, since 70% of production in 2021 came from just one country, the Democratic Republic of Congo. Cobalt production is also associated with a complex web of issues around small-scale mining, child labour, and modern slavery.

Additional technical disadvantages of LIBs are that they can only be safely transported and stored while partially charged, and that charging at temperatures below 0 °C is usually very slow and can permanently damage the battery.

It is possible to construct LIB cathodes using iron (LFP, lithium iron phosphate) and manganese (LMO, lithium manganese oxide), among others. This often leads to worse performance in some sense but batteries made with these cathodes still find applications. The theoretical maximum energy density of LIBs using LFP cathodes is about 225 Wh/kg, while the same value for LIBs using LMO cathodes is about 310 Wh/kg[20].

The mining of lithium is very water intensive and the small number of suppliers can lead to bottlenecks or price fluctuations [16] [17]. It bears mentioning that it might be possible to produce lithium from geothermal brines in the near future, and this is expected to be much more sustainable. Reserves of lithium-rich brines have been found in Europe, including the United Kingdom (South-West and North-East England)[18]. Typical lithium ion batteries have an energy density of about 270 watt-hour per kilogram (Wh/kg) at prices of around

[16] P.W. Gruber et al. Global Lithium Availability - A Constraint for Electric Vehicles? *Journal of Industrial Ecology* 15/5 (2011) 760-775

[17] J. Speirs et al. The future of lithium availability for electric vehicle batteries. *Renewable and Sustainable Energy Reviews* 35 (2014) 183-193

[18] B. Sanjuan et al. Lithium-rich geothermal brines in Europe: An up-date about geochemical characteristics and implications for potential Li resources. *Geothermics* 101 (2022) 102385

100 USD/kWh[19]. The theoretical maximum capacity of LIBs is about 310 Wh/kg[20].

LIBs contain materials that are either in relatively short supply or otherwise precious, so it is crucial that spent batteries are either reused or recycled. Although batteries eventually become completely unusable, in many cases they stop being used once they merely become inefficient for a certain task, like EV batteries. EVs have started to see widescale adoption recently. The EV stock of the United Kingdom is expected to rise to about 16 million by 2030, which means used batteries will become a significant issue in the coming decades.

High quality data about battery longevity is limited. Nonetheless, according to data from a number of Tesla owners, battery capacity only reduced by about 10% after 200,000 miles driven. While researchers at Stanford University found that retired EV batteries retain 70-80% of their original capacity. More data is needed to see what condition EV batteries are going to be in when they stop being viable as car parts. Nevertheless, it is expected that giving used batteries a second life is likely to be an important alternative to recycling for a portion of EV batteries. One potential second use for EV batteries would be to use them in grid scale energy storage.

Of course, even batteries given a second use will eventually reach a stage where they are no longer usable in any application. At that point, most batteries are recycled or landfilled. Putting lithium ion batteries is landfill would be remarkably wasteful considering how much precious raw materials and industrial effort goes into making them. Recycling on the other hand extracts the precious materials, mainly the metals from the cathode, in a form that makes them usable in new cathodes.

The main ways of recycling are pyrometallurgy, hydrometallurgy and direct recycling. Pyrometallurgy is an established way of recycling LIB cathodes, but it leads to a material called black mass, which needs to be processed, before it

[19] J. T. Frith et al. A non-academic perspective on the future of lithium-based batteries. *Nature Communications* 14, 420 (2023)

can be used in making new cathodes. This is the cheapest and simplest recycling method, but it also generates the most waste and it does not recover the lithium content. Hydrometallurgy is similar to pyrometallurgy, although it is more complex and more expensive, it leads to much less waste and a higher quality end product. In direct recycling the battery cell is disassembled, and its parts are directly used in constructing new cathode materials. This recycling method is the most complex and most expensive, but it also recovers the largest portion of precious materials from the cathode and thus leads to the highest quality product.

Battery energy storage in Northern Ireland

There are only a few operational battery energy storage sites in Northern Ireland for now. For example, Northern Ireland Water has a 4.1 MW battery storage site at Dunore Point, which stores energy from the onsite solar farm, and another similar solar powered battery storage at the Ballykelly Wastewater Treatment Works.

5.4 Electric vehicles as means of energy storage

The battery of an EV is no different from other types of battery energy storage but this application is so different from grid scale energy storage solutions that it deserves its own section. The following section gives an overview of using EVs as a mobile fleet of batteries.

Vehicle to grid (V2G) energy storage

The average car spends the vast majority of its time being parked somewhere, it is only used in about 4% of the time. It makes sense then to think of electronic vehicles (EV) as a fleet of small-scale battery storage sites through which higher efficiency utilisation of renewables can be achieved. That can be done by encouraging owners to recharge their batteries at times of high renewable production and low overall energy demand (for example, overnight) or even to sell energy to the grid at times of low EV usage and high overall energy demand. The former is called “smart charging”, and the latter is usually referred to as “grid services”.

The last 15 years has seen a remarkably fast adoption of plug-in hybrid, fuel cell and battery electric EVs. According to a 2024 International Energy Agency report, the global EV stock went from 116,702 in 2011 to 50,066,000 in 2023. Northern Ireland is following a similarly steep trend, albeit at a much smaller scale: the region's EV stock went from 22 in 2011 to 22,804 in 2023.

According to a 2022 United Kingdom Government Department for Transport statistical dataset, the current average battery capacity is 50 kWh, which means that the entire EV stock in Northern Ireland has an approximate combined capacity of about 1 gigawatt-hour (GWh). For reference, 1 GWh would be enough to power all of Northern Ireland for an hour at an average energy demand of about 1 GW at the 17:30 peak, so the current EV stock is already significant on a regional scale.

Vehicle to grid (V2G) energy storage is expected to play a significant, but secondary role in the efficient usage of renewables in the future. The value of V2G storage strongly depends on user behaviour, and requires some specialised equipment like smart meters and smart chargers. Nonetheless, according to an Energy Systems Catapult report, most of the value offered by V2G storage can be utilised by keeping EVs plugged in as much as possible and also by charging them at times of high renewable production and low overall electricity demand.

5.5 Relevant emerging technologies

There are few research areas that garner as much attention as energy conversion nowadays, meaning the transformation of some type of energy into electrical energy and vice versa. There are two promising technologies that are worth mentioning in the context of large-scale energy storage: sodium ion batteries (SIBs), and vanadium redox flow batteries (VRFBs).

Sodium ion batteries

The working principle and cell design of SIBs are very similar to that of LIBs, which means that they are often interchangeable. For example, it is possible to construct 18650 SIB cells, which is the most common cell type for LIBs. This means that batteries based on SIB cells would not need completely new designs, and even that LIB and SIB cells could be mixed in the same battery pack.

The main advantage of SIBs is that cathode materials are most often made from cheap, abundant and relatively non-toxic metals like iron, titanium and manganese. Additionally, sodium itself is much more abundant and evenly spread on Earth than lithium. That means that SIBs generally come with a significantly lower supply risk and are expected to be 10-30% cheaper[20].

Although SIBs are only just entering commercial usage, there is already some research about their potential recycling[21]. The main issues SIBs face in terms of recycling are mostly the same as the ones for LIBs. One unique issue SIBs have is that cells are made using cheaper and more abundant materials, which means the value that can be recovered through recycling is lower than in the case of LIBs for example. Strategies will need to be developed in order to overcome this economic barrier either by simplifying recycling processes or designing batteries for easy recycling in the first place.

The only commercial example of a SIB used on a large-scale at the time of writing is CATL's EV battery, which has an energy density of 160 Wh/kg, at a cost of 77 USD/kWh. The theoretical maximum energy density of SIBs is expected to be around 300-350 Wh/kg.

Vanadium redox flow batteries

The other emerging technology that bears mentioning is vanadium redox flow batteries (VRFBs). The main advantage of VRFBs is that the main component, vanadium, does not degrade over time, unlike the cathode material of a battery. Additionally, the most important advantages of VRFBs are low operating cost,

[20] K. M Abraham Prospects and Limits of Energy Storage in Batteries. *The Journal of Physical Chemistry Letters* 6 (2015) 830−844

[21] Y. Zhao *et al.* Recycling of sodium-ion batteries. *Nature Reviews Materials* 8, 623–634 (2023)

very low emissions, and the possibility of energy storage with minimal or no loss on a much longer time scale than other chemical energy storage methods.

Whereas the most important disadvantages of VRBFs are high capital cost, low energy density and the fact that most electrolytes are very corrosive and can damage the cell over time[22]. A significant additional disadvantage is the usage of vanadium, which presents potentially serious supply chain issues. Vanadium is not rare, it occurs all around the world, but usually only in small concentrations, which makes extraction difficult. The three main vanadium producers in 2022 were China, South Africa and Russia, collectively making up of 96% of global production, of which 70% comes from China. The low number of suppliers can lead to bottlenecks and significant price fluctuations, and the fact that vanadium is also used as an important steel component further increases competition.

There are proposed alternatives for vanadium to be used as charge carriers in redox flow batteries, such as organic molecules, or iron and manganese compounds.

Despite the noted challenges, there are commercial examples for VRFBs, like the Energy Superhub in Oxford, United Kingdom. Due to the fact that VRFBs only entered commercial usage in the last few years, these should be thought of as proof of concept projects, where long-term performance can be tested in a realistic setting.

6 Concluding remarks

The past three decades saw the introduction of international agreements and government legislation and policies aiming to meet net zero targets that seek to address climate change. Among the most impactful have been the initiatives seeking to decarbonise industry and transport. Countries have set out their

[22] K. Lourenssen, et al. Vanadium redox flow batteries: A comprehensive review. *Journal of Energy Storage* 25 (2019) 100844

individual climate change legislation, strategies and schemes, outlining how they are planning to implement decarbonisation in the noted sectors.

The main way countries support the development of renewables is through the introduction of subsidy schemes that reduce the initial capital cost of developments and the price of electricity once production begins. In the wider United Kingdom and the Republic of Ireland the current subsidies are all contract for difference type schemes. Northern Ireland also has plans to introduce a contract for difference scheme.

The sections of the United Kingdom's economy linked to the highest carbon emissions are transport, energy and the upkeep of buildings. In recent years, the United Kingdom's Government chose to address all of these by increasing the share of renewables in the energy mix and implementing electric solutions where previously fossil fuels have been used. For the whole of the United Kingdom, and Northern Ireland specifically, the most abundant source of renewable energy is by far wind energy; the region is suitable for both onshore and offshore developments.

On 4 July 2024, there was a change of government in the United Kingdom, and while it is too early for any large-scale policy changes, the incoming Secretary of State for Energy Security and Net Zero has set out some key priorities which might impact the renewables landscape of Northern Ireland, in addition to decisions made by the Northern Ireland Executive. The upcoming elections in the Republic of Ireland in March 2025 also could influence the policy landscape of renewables there, as well as on the whole island of Ireland.

As this Paper also explains – at section 4 - the main challenge of wind energy is that its daily production peaks do not reliably coincide with the population's daily energy demand peaks. This makes energy storage necessary in order to maximise the efficiency and effectiveness of wind use.

As explained earlier in the Paper, there are broadly two types of energy storage: mechanical and chemical. The most relevant mechanical energy storage methods for Northern Ireland are pumped hydro and compressed air energy storage. Both methods work by forcing some material into a higher energy state using surplus energy, which can then be used to generate electricity at times of high energy demand. Mechanical energy storage methods tend to have high capital costs and long lead times, but once a project is finished it provides relatively cheap energy storage for decades with minimal upkeep. The main drawback of these energy storage methods is that they require specific types of geology.

Chemical storage most often refers to hydrogen generation or some type of battery. Both of these are relevant for Northern Ireland due to the abundance of wind energy. Hydrogen is already a very important part of most national economies, but only on a relatively small-scale, and its production is based on fossil fuels in the vast majority of the cases. The ideal production method for hydrogen is electrolysis of water using renewable electricity, but this is quite expensive at the moment. Hydrogen is currently not expected to become a universally used fuel, but there are some promising areas where it is the ideal way of decarbonisation, like steelmaking and long-distance shipping and aviation. As such green hydrogen is a potentially significant route of decarbonisation.

The widescale electrification of transport and industry are integral parts of most countries' net zero plans, and Northern Ireland is no different. Such energy use requires a country's large upscaling in battery production and utilisation. The most important battery types in this regard are lead-acid and lithium ion batteries. The fundamental chemistry of a battery defines its technical and economic parameters like energy density, cost, durability and safety. Both for the electrification of transport and industry lithium ion batteries are expected to be central. Lithium ion batteries provide some favourable technical properties, although they tend to be relatively expensive and their components are associated with supply chain issues. The current upward trend in the adoption of EVs is expected to continue, or even accelerate, which means EVs are expected to play a significant role in decarbonising industries and transport. This is not only expected to displace fossil fuel usage, but also see usage of EVs like a fleet of small-scale energy storage system on a country-wide scale.

Going forward, all the energy storage methods noted in this Paper are key to implementing commitments and requirements set out in international agreements and individual countries' legislation, strategies and schemes, when seeking to efficiently and effectively address climate change.