Energy Systems Roadmapping for Ireland: **REPORT 1**

NEXSYS

Executive Summary

The primary objective of the NexSys programme is to investigate pathways towards a decarbonised energy system. In recent years, considerable progress has been made in defining policies and targets focused on greenhouse gas emissions reductions in Ireland. However, considerable gaps remain in meeting national carbon emissions reduction goals, with emissions across all sectors projected to exceed the ceilings set for 2030. The NexSys programme incorporates four strands of research – Transport, Cities & communities, Water, and Offshore Wind – in addition to the core Energy Systems hub, to deliver state of the art research from seconds to seasons. A model of the operation of the system to investigate the impact of different technologies, technology adoption levels and operation strategies on the supply-demand balance has been developed. The NexSys modelling approach to model Irish electricity generation combines unit commitment and investment and planning models (Figure ES.1). Additional models are used to model households and electricity grids that enables a comprehensive overview of the system from policy and market design to electricity generation, transmission, storage, and household energy-using technologies.

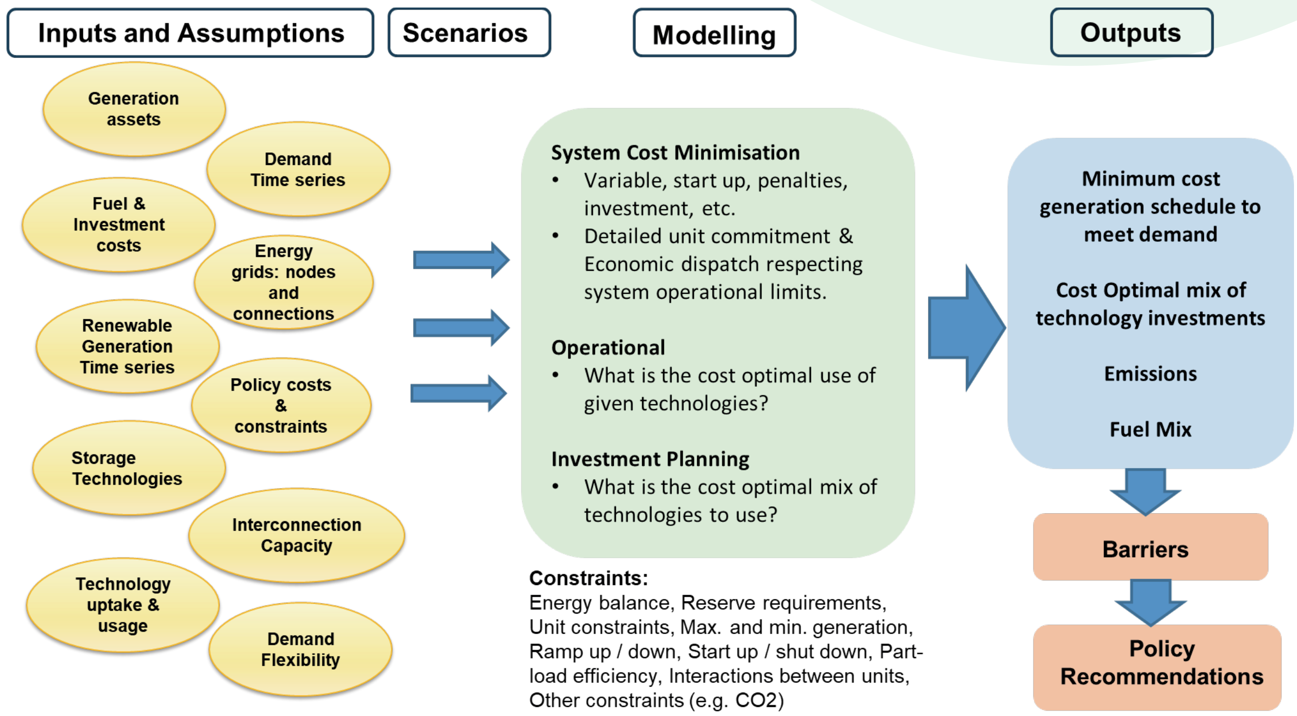

Figure ES.1: Overview of modelling approach used to underpin the roadmapping activity.

across sectors in the decarbonisation of the energy system. In this first roadmap of the series, we focus on the efficient and effective decarbonisation of the electrical energy system, considering that increased electrification with very significant expansion of generation from renewable energy sources (RES) is the primary strategy underpinning climate action in Ireland and other countries.

In Ireland the decarbonised electricity system will rely heavily on generation from variable renewable sources such as wind and solar. In such a system, with weather-dependent generation, a key consideration is how to ensure the matching of generation to demand over time scales ranging

The aim of the modelling is to take inputs in terms of generation capacity, technology characteristics and demand and through a cost minimisation process produce the generation schedule which meets demand at least cost. The initial focus is on understanding power system operation in 2030 with ongoing extension to the decarbonised system. The modelling results show that conventional gas generation will still have a major role to play in the electrical system by 2030. This generation plays a vital role in providing backup in times of low renewables, providing flexibility (up to 70%) to the system to help balance supply and demand and crucially providing system services which are essential to the secure operation of the system.

The complete removal of such conventional generation therefore presents problems for the stable operation of the electricity system. However, the reliance on this generation is clearly a barrier to decarbonisation and alternatives must be found. Technologies such as grid-forming converters, synchronous condensers, and clean flexible generation are all part of the solution.

Improved matching of generation with demand can be achieved by changing demand patterns to better match with periods of high generation, referred to as demand-side flexibility. Considerable opportunities for flexibility exist in the electrification of heating, transport and industrial processes. Modelling results suggest that a portfolio of different flexibility sources will be required and that such flexibility can indeed increase the use of renewable generation. The opportunities for increased flexibility from new technologies such as vehicle-to-grid remain to be fully characterised and quantified. It is also important to note that the opportunities for the exploitation of such flexibility will not necessarily be realised without putting appropriate incentives in place to encourage their provision.

While achieving more flexibility on the demand-side can certainly help increase the use of renewables, this flexibility is unlikely to solve all supply-demand balancing issues. Modelling suggests that even making use of considerable demand-side flexibility by 2030, there will still be an excess of renewable energy in the system at certain times. There is a clear opportunity here to find ways to best use of this excess generation, which balance cost and effectiveness in emissions reductions. Increased use of storage with the ability to store energy over periods ranging from hours to months and maybe years is an important approach. Long-duration storage with the capability to store energy for long periods of time and use it during extended periods of low renewable generation will be an important part of the future decarbonised energy system. Quantification of the capacity requirements for such long duration storage based on analysis of the frequency and duration of periods of low renewable generation remains an important question to be addressed. In addition, technology costs for long duration energy storage are still high, so appropriate economic incentives will be important to encourage investment.

Green hydrogen is usually seen a major component of decarbonisation efforts. The research has shown the potential for its use as a clean fuel in heavy duty transport, in blending in the gas network, and for long-duration storage and associated clean dispatchable electricity generation. Considering the cost and demand projections for green hydrogen technology, it is unlikely however that hydrogen will play a significant role until post 2030. Therefore, further research is needed to better understand its most economically feasible end-uses in the energy system and the potential interplay between such end uses. Quantifying green hydrogen demand and end-uses is a key area for further research. The feasibility of plans concerning the expansion of offshore wind will be very dependent on providing a route to market for excess electricity generated and the production of green hydrogen has the potential to provide one such route.

In addition to the technical and economic issues associated with the move to a decarbonised energy system, social issues are also of significant importance. An important underlying assumption in decarbonisation pathways is the widespread adoption of low carbon technologies, such as heat pumps and EVs. But there can be real barriers to this adoption and the high rates of adoption required to meet targets is by no means guaranteed. Therefore, gaining an understanding of people's attitudes to such technologies and hence an understanding of the barriers and potential incentives necessary to overcome those barriers is important. The modelling of adoption rates by means of models calibrated by survey data collected from households is ongoing work which will form the basis for including informed technology adoption rates in the development of scenarios.

Implementation of decarbonisation strategies can involve changes which have a real and significant impact on people's lives. The concept of the Just Transition has emerged to capture the idea that such changes should be done in a way that protect the livelihood of people and their communities. Using the case of the closure of peat processing in the Irish Midlands as a case study, research in NexSys has highlighted a gap between theory and practice. The work points to the importance of establishing a clear process for practical implementation of the theoretical concepts behind the just transition.

This first instalment of the NexSys Roadmap describes the key elements of the pathway to decarbonise our electricity system and some of the research results of the programme so far. Future chapters will include more detailed outputs on the contribution of individual sectoral strands to energy system decarbonisation. Collectively, the NexSys Roadmap publications will provide a comprehensive set of solutions to the technical and societal challenges to attain a net zero carbon energy system.

Table of Contents

1. Introduction

The NexSys programme is an all-island, multidisciplinary energy research programme which brings together researchers and industry with the goal of defining pathways to a net zero energy system. The programme is structured around five strands of research: Energy Systems, Transport, Cities and Communities, Offshore Wind and Water-Energy nexus.

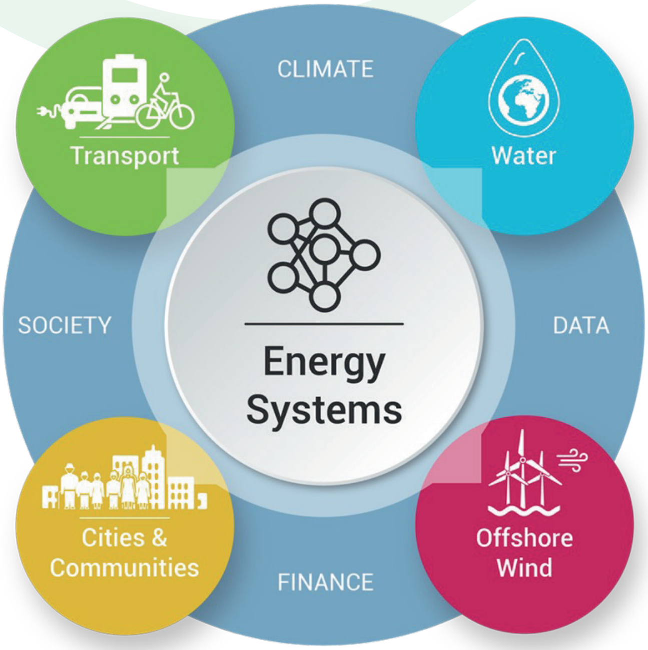

Figure 1.1: NexSys Programme Structure

Within the overall NexSys programme the Energy Systems strand brings together researchers with a focus on technical, economic and social aspects of the energy system. The high-level objective is to determine how energy systems should evolve in order to achieve increasing renewable energy shares in electricity (RES-E) towards 2030 and subsequently the net Zero carbon goal by 2050. The research involves cross-disciplinary research in engineering, mathematics, economics, and the social sciences to understand aspects covering power system operation, dynamics, power electronic devices, hydrogen transport and infrastructure, markets, finance, and environmental psychology organised across eight work packages. The roadmapping activity provides an integration mechanism for this diverse research. It leverages a considerable body of existing research by NexSys researchers which sets the foundation for the NexSys research programme.

The objective of the Roadmap is to help identify pathways towards a decarbonised energy system. It compiles important aspects of the detailed research carried out in NexSys strands and workpackages and demonstrates the application of the outputs to the Irish system. The Roadmap outcomes are underpinned by a modelling activity which is used to quantify the impact of various technologies and behavioural changes on the decarbonisation of the energy system. The modelling activity helps identify barriers and bottlenecks in the pathway to net-zero.

The outputs of the roadmapping activity will be described in a series of annual reports. This report is the first such report and therefore it focuses on describing the methodology used for the roadmapping, reviews relevant research from the NexSys team to date and identifies some of the main topics for further research. The focus of this report is on the electrical energy system given its central role in the policy drive towards a net zero energy system.

The structure of this first Roadmap is as follows: To set the scene and provide context for Irish energy system decarbonisation, Section 0 provides a very brief overview of some of the main national policies and strategies that have been developed in recent years. Section 3 describes NexSys modelling based on the development of detailed operational and investment planning models for the Irish electricity and gas systems. It also includes preliminary results from the modelling exercise to facilitate a discussion of what are viewed as some of the important issues relating to the Irish energy system. Section 4 presents a review of some of the NexSys research of particular relevance to the goals of the road mapping exercise. Finally Section 5 presents some of the directions for the research which will be explored further in future roadmapping activities.

2. Overview of Targets, Policies and Current Status

Recent years has seen considerable activity in the development of strategies and roadmaps for the Irish energy system. Many of these have set targets for 2030 as major milestones on the path to net zero carbon in the energy system.

The Climate Action and Low Carbon Development (Amendment) Act 2021[1] set out the national climate objective of achieving the transition to a "climate resilient, biodiversity rich, environmentally sustainable and climate neutral economy" by no later than the end of 2050. The act also sets the interim target of reducing the annual greenhouse gas (GHG) emissions in 2030 to 51% of the GHG emissions recorded for 2018.

Emissions reductions are further specified in the legally binding carbon budgets and sectoral emissions ceilings set by the Government on July 2022[2]. The carbon budgets set out the total emissions allowed by the country over each of three successive 5 year periods from 2021 to 2035. The sectoral emissions ceilings set out the maximum amount of greenhouse gas emissions that are permitted in different sectors of the Irish economy. The ceilings are set in terms of carbon emissions (millions of tonnes of carbon dioxide equivalent, MtCO2eq) for the sectors of Electricity, Transport, Built Environment, Industry, Agriculture, LULUCF (Land Use, Land Use Change and Forestry) and others (F-Gases, Waste & Petroleum refining).

As a member of the European Union Ireland also has commitments to achieving the European climate objectives. It is worth noting that the legally binding national targets set out in the Climate Action Act and sectoral emissions ceilings have different base years and hence different targets compared to the European level targets of reducing net greenhouse gas emissions by 55% (relative to 1990 levels) by 2030. The overall EU emissions target and actions are split between (i) the EU Emissions Trading Scheme, which contains the electricity, heavy industry, heat production, and aviation sectors with an EU-wide target of 62% reduction, and (ii) the National Effort Sharing Regulation (ESR) which requires a 42% reduction in emissions compared to 2005 levels by 2030.

The targets and actions required to meet the Irish climate and emissions objectives for 2025 and 2030 are captured in the Climate Action Plan (CAP)[3], the first was published in 2019 with the most recent updated version in May 2024. The CAP outlines a set of strategies and actions designed to progress towards the target of reducing Irelands greenhouse gas emissions by 51% by 2030 (relative to 2018 levels) and achieving net-zero no later than 2050. The plan applies to all sectors including Electricity, Industry, Built Environment, Transport, Agriculture, Land Use and Forestry, etc. Some key targets related to the energy system include an 80% share of renewable electricity by 2030, 500,000 retrofitted homes and installation of 680,000 heat pumps by 2030, and for the transport sector a 20% reduction in vehicle kilometres travelled and a 50% reduction in fossil fuel usage.

The electricity system is a central enabler for achieving the emissions reductions targets. The main strategy for emissions reductions in the transport and built environment sectors in Ireland relies on electrification of heating and transport. Underpinning this is the decarbonisation of the electricity system and hence a shift to renewable energy sources of electricity. The Climate Action Plan sets a target for 80% of electricity to be generated from renewable sources by 2030. EirGrid the Irish Transmission System Operator (TSO), in collaboration with SONI (the TSO in Northern Ireland), have produced a roadmap for the electricity system[4] which outlines a pathway for the electricity system to meet the 2030 targets. The roadmap covers actions relating to transmission system development, system operation, markets, engagement with industry and the public and security of supply. EirGrid have also conducted the *Tomorrows Energy Scenarios*[5] study which explores scenarios beyond 2030 and for achieving the net zero targets for 2050.

The large scale expansion of offshore wind is set to play a major part in the future of the Irish energy system. The *Future Framework for Offshore Renewable Energy*[6] sets out the pathway Ireland will take to deliver 20 GW of offshore wind by 2040 and at least 37 GW by 2050. The current installed capacity of offshore wind in Ireland is 25 MW and the target for 2030 contained in the Climate Action Plan is 5 GW. An important milestone on the way to achieving this was the awarding of 3 GW capacity under the first offshore wind auction in 2023.

Related to the very significant expansion of renewable electricity generation is the need for increased interconnection between Ireland and other European countries. The National Policy Statement on Electricity Interconnection envisages increased expansion of interconnection with the UK and France further potential interconnection to countries such Spain, Belgium and the Netherlands.

There is also considerable emphasis on the role that indigenously produced green hydrogen can play in the pathway to net-zero emissions by 2050. The *National Hydrogen Strategy* published in July 2023[8] considers the harnessing of the offshore renewable potential in Ireland to produce green hydrogen and the creation of a domestic and export market for green hydrogen. The initial shorter-term focus is on the production of green hydrogen from grid connected electrolysis using curtailed renewables with expansion to the production of hydrogen from offshore wind in the longer term. Heavy duty transport is identified as one of the first end uses with employment in industrial flexible power generation and export following later.

Other recent strategy documents include the strategy for the use of biomethane[9] in decarbonisation efforts, the Roadmap for the *Decarbonisation of Industrial Heating*[10], and a policy on sustainable transport[11].

The overall long term approach to achieving climate neutrality by 2050 is outlined in the recent report describing Irelands long term strategy on greenhouse gas emissions[12]. This report summaries the main pathways to climate neutrality by sector, quantifies the level of investment needed and discusses the aspects of finance, citizen engagement and just transition.

Despite the very considerable activity focussed on emissions reductions and related policy, achievements to date and the projections for actual reductions based on existing measures suggest that targets will not be met. The Environment Protection Agency reports annually on progress towards achievement of emissions targets and provides projections up to 2030. The latest analysis from May 2024[13] indicates that considering existing measures across all sectors, Ireland will achieve an 11% reduction compared to the 2018 levels which is considerably off the 51% reduction target. Even with the additional measures implemented as detailed in CAP 2024 a reduction of only 29% could be achieved. Therefore as of now, the sectoral emissions ceilings are projected to be exceeded across all sectors in 2030.

2.1 The Net Zero-Carbon Energy System

Considering the focus and directions outlined in the various strategy and policy documents a high-level picture emerges of the features of a net-zero energy system in Ireland. These features are summarised for each of the main sectors in the diagram in Figure 2.1.

One aspect of the general strategy which is very clear is that the electrical energy system will play a significantly expanded role in the net-zero energy system. The SEAI *Energy in Ireland Report 2023*[14] shows that electricity accounted for approximately 22% of total final energy consumption in 2022 comprising 31 TWh of the energy demand out of a total energy demand of 140 TWh. As indicated in Figure 2.1 a net-zero scenario requires the electrification of heat and transport, with electricity supplying a much larger portion of final energy demand in these sectors. Although there is a great deal of uncertainty in predicting the figures for electrical demand decades into the future several studies have made projections. EirGrid's *Tomorrow's Energy Scenarios* predict a 2050 electrical energy demand between 70 TWh and 85 TWh, depending on the scenario. The study by MarEI and Wind Energy Ireland[15] which modelled a net-zero scenario suggested that by 2050 electricity would account for approximately 80 TWh out of a total of 108 TWh, i.e. 74% of final demand.

It is also worth noting that the net zero system envisages a strong role for fuels derived from electricity though power to gas, e.g. in powering heavy goods and maritime vehicles and in aviation and industrial heating. For example the ENTSOE TYNDP scenarios for Ireland in 2050 envisage somewhere between 58 and 64 TWh of electrolyser load by 2050. The EirGrid TES assumes a 2050 hydrogen demand mainly from transport and industry of 14 TWh. Therefore the electrical energy system is envisaged either directly or indirectly to provide most of the energy needs in the net-zero scenario.

The electricity system will play an increasingly important role in Ireland's net-zero carbon future and it is the primary focus of the NexSys programme. Notwithstanding the opportunities provided by the electricity system to reduce carbon emissions from energy in Ireland, many technical

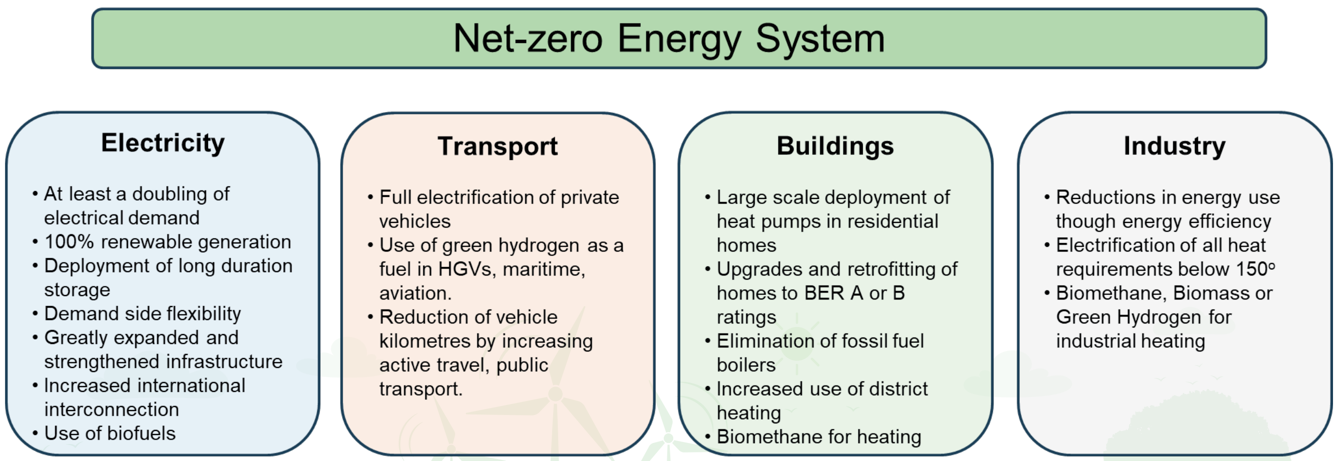

Figure 2.1: Features of a net-zero energy system in Ireland summarised from the various strategy and policy documents.

and societal challenges remain, both in increasing the electrification of the energy system and the attainment of a fully renewable electricity system. The NexSys Roadmap series focuses on addressing these challenges by presenting the results of state-of-the-art systems-based research in future electricity systems with an interdisciplinary perspective. n summary therefore the electrical energy system is envisaged either directly or indirectly to provide most of the energy needs in the net-zero scenario.

3. Electrical Energy System

Considering the central role that electrification plays in emissions reductions the initial modelling focus has been on the electrical system and in particular on the secure and stable operation of the power system as renewable generation levels increase and electrification of the heating and transport sectors progresses. In this section the modelling methodology used to underpin the Roadmap is briefly explained and some of the initial results are used to highlight some of the challenges.

The Irish all-island power system is an isolated system with a relatively low level of interconnection to other systems (e.g. currently peak demand in the system is approximately 7 GW and there are two interconnectors to the UK with a peak capacity of 1 GW). Current and future interconnectors to other countries use a non-synchronous High Voltage DC (HVDC) connection. The system already has a relatively large penetration of renewable generation with 40% (approximately 35% from wind) of demand in Ireland supplied from renewable sources in 2023. Currently the renewable generation is largely from onshore wind farms, although generation from offshore wind and PV is set to grow significantly over the coming years. The 80% RES-E target for the Irish system by 2030 implies that for some of the time, instantaneously the portion of demand supplied from variable renewable generation will come close to 100%. In the net zero scenario it is likely that the system will be largely based on variable renewable generation most of the time.

The general challenge for any system relying on variable renewable generation is associated with the balancing of supply and demand across a wide range of time horizons from sub-second to months and years. Thus different forms of storage and flexibility from the demand side becomes vitally important in the system to aid with balancing. Energy storage systems capable of storing large quantities of energy in a cost effective manner over different time durations are needed, with the obvious aim of storing energy from periods of high renewables for use during periods of low renewables. Battery storage has proved quite effective at storing electrical energy for periods of hours. However there is also a need for longer duration storage to store energy for days, weeks, months or years to deal with potential extended periods of low renewable generation. Flexibility from the demand side can also be used to aid with balancing by shifting demand, for example away from peak demand times or to times of high renewable generation.

In addition to its variability generation from wind and solar is also inherently different from conventional generation in how it connects to the power system. Electricity generated from wind and solar farms is delivered to the grid through power electronics converters which use programmed control algorithms to define how the generation behaves and reacts to any changes in the overall system. This type of generation is referred to an non-synchronous generation. In the way it is currently operated this non-synchronous generation lacks some important characteristics which could previously be assumed to be inherently supplied from conventional generation. These characteristics, such as the provision of inertia, fault currents, and reserves have always been relied on for the stable and secure operation of the power system. In Ireland the system operational changes and new system services introduced under EirGrid's DS3 Programme have been instrumental in dealing with accommodating the high levels of variable renewable generation for the 2020 targets. However operating an isolated system with an almost complete reliance on non-synchronous generation represents a major challenge not yet achieved at scale anywhere in the world.

Because of the isolated nature of the Irish system and its future reliance on very high levels of non-synchronous variable renewable generation, realistic projections for levels of renewable generation which can be accommodated need to account for the issues relating to stable and secure operation and in particular how and from where necessary support services are to be provided. In any modelling approach it is therefore necessary to account for sufficient operational detail in the modelling of the system. This detail needs to capture operational constraints necessary for the secure and reliable operation of the system in the absence of conventional generation. For example one issue of considerable importance is the need to maintain stability of the system in the absence of the inertia usually provided by conventional generation. The need to ensure the provision of adequate generation reserves is another issue. The constraints imposed by such operational issues can limit the amount of renewable generation which can be used in the system at any given time. Failure to include these details can lead to an overly optimistic estimate of the level of renewable generation achievable.

3.1 Modelling Methodology

Figure 1.1 shows a high level overview of the modelling approach from inputs to outputs. At the heart of the modelling approach is what is often referred to as a "unit commitment" model of the Irish system. This model uses an optimisation algorithm to find the least cost set of generation assets which satisfies demand and other system constraints over a defined time window. Inputs to the model consist of projections for demand, projections for generation from different sources plus their associated technical characteristics and costs, interconnection and storage capacities and the definition of system constraints. The model can output the generation, interconnection and storage schedules which meets the demand (or indicate if demand cannot be met), and an associated estimation of costs, emissions, and excess renewable generation. The model is developed using the open source energy systems modelling platform Spine[16]. The use of an open-source tool allows easy sharing of models and data and results between researchers and facilitates implementation of new technologies and constraints in the modelling procedure.

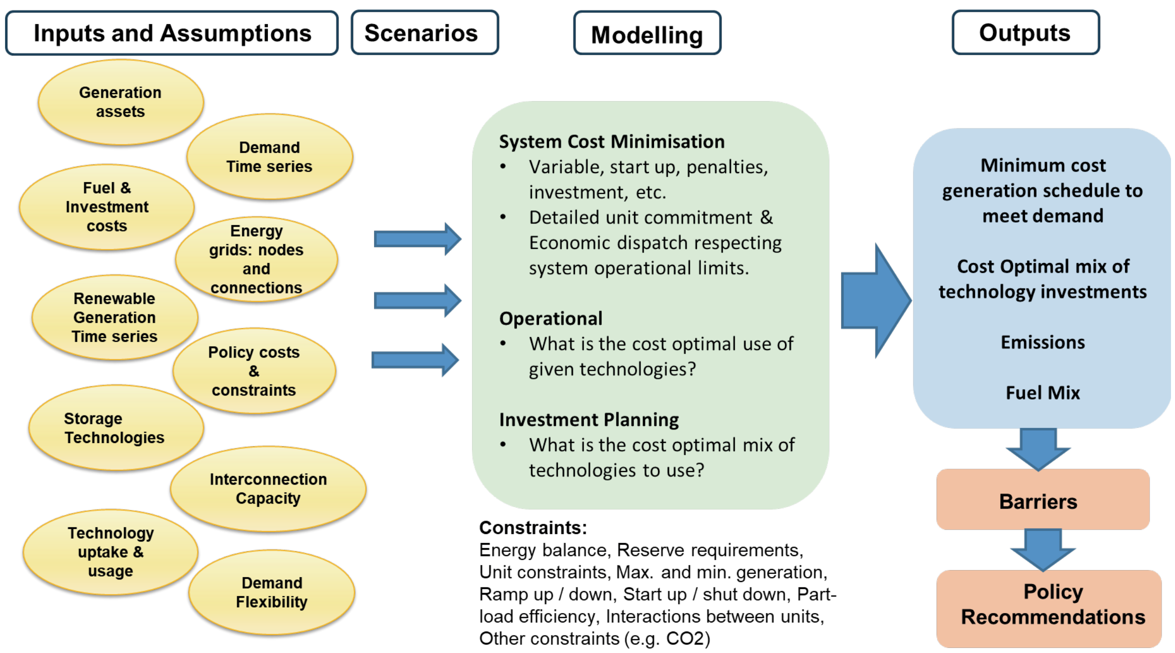

Figure 3.1: Overview of modelling approach used to underpin the roadmapping activity. The aim of the modelling is to take inputs in terms of generation capacity, technology characteristics and demand and though a cost minimisation process produce the generation schedule which meets demand at least cost.

As an example of the outputs from the model Figure 3.2 shows results from the modelling of one week in 2030. The figure shows the projected hourly demand for the week in 2030 (red curve) and the lowest cost set of generation assets used to satisfy that demand while also satisfying system operational constraints. The generation assets in the system are consistent with the targets for 2030 in terms of onshore and offshore wind and PV, as are the battery storage capacities, interconnection levels, and system operational constraints. This example shows a week where there is sufficient renewable generation to meet demand and also to facilitate exporting of energy on the interconnectors to UK and France. In fact for this week there is also considerable excess renewables which the system cannot use in the absence of any form of long duration storage. It is also worth noting that there is a minimum level of conventional generation currently required in the system at all times, even if there is sufficient renewable generation to meet all demand. This is to satisfy system operational constraints relating to system stability. Specifically there is a need to maintain sufficient conventional generation in the system in order to maintain a minimum level of system inertia. This requirement can act as a barrier to the removal of conventional generation. This model has assumed that the inertia is provided by conventional generation which reflects the current situation. However EirGrid are in the process of procuring low carbon inertia services, i.e. procuring inertia from technologies other than conventional generation which will have a major impact on the ability to replace more conventional generation with renewable generation.

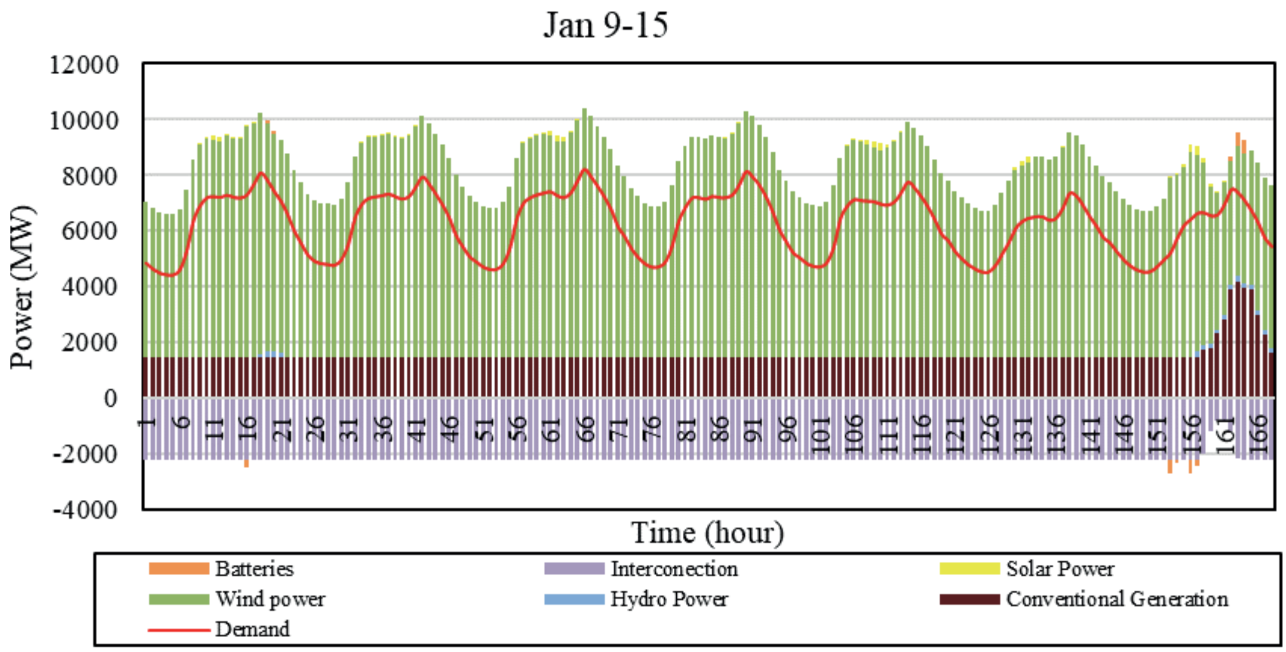

Figure 3.2: Illustrative example of a representative week in 2030 when there is sufficient renewable energy to meet demand.

Figure 3.3 shows the demand and generation for another week in 2030 where renewable generation is not sufficient to meet demand. In this case a considerable level of conventional generation must still be called on to meet demand which illustrates the continued importance of conventional generation in the system in the medium term.

It is important to note that when dealing with projections for future years there are considerable uncertainties in many of the inputs which can have a significant impact on the model outputs. Obvious uncertainties relate to the production from wind and solar for any given year and demand growth which depends on many factors relating to the economy and uptake of electrification of heating and transport. Other important uncertainties relate to flows on the interconnectors between Ireland and UK and France which depend on markets and trading arrangements. In the time scale of 2030 many targets for renewable generation and electrification of heating and transport have been defined, which provide a good baseline for model inputs. However beyond 2030 targets are less defined leaving considerable scope for the definition of various scenarios to cover a range of uncertainties. An important objective of the

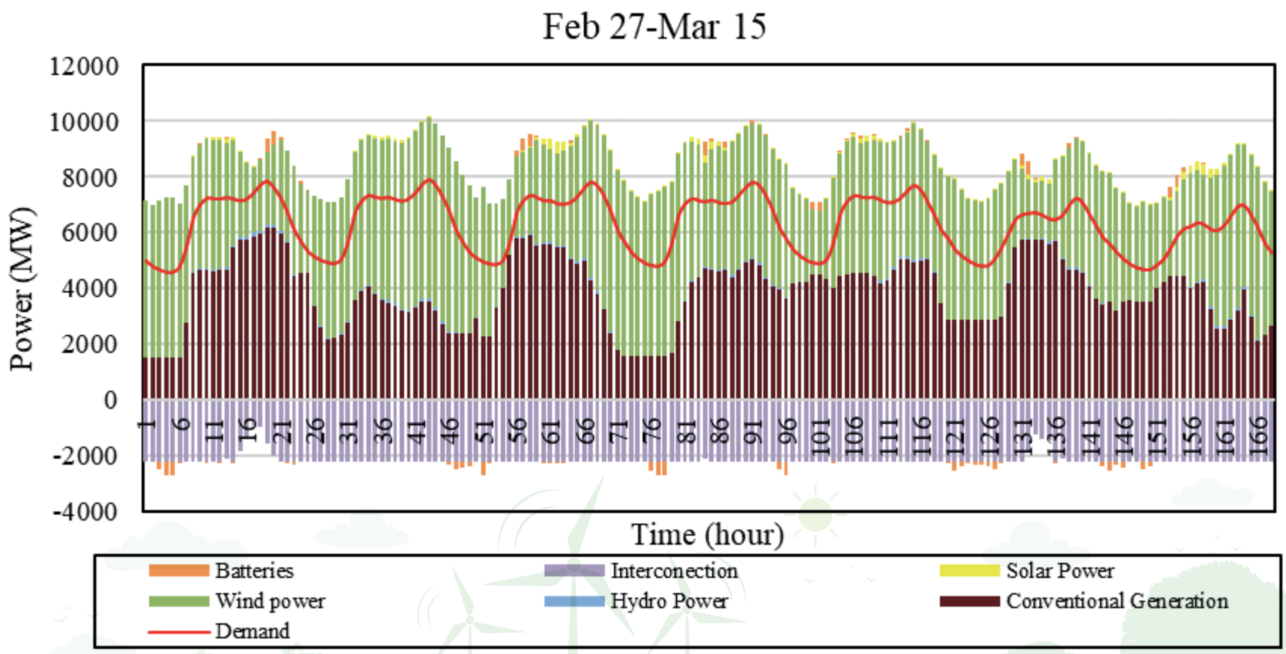

Figure 3.3: Illustrative example of a representative week in 2030 when there is insufficient renewable energy to meet demand.

roadmapping activity in NexSys will be to better quantify such uncertainties by leveraging the detailed research work in the NexSys programme.

The above two examples illustrate the difficulties of matching supply and demand when a large portion of the supply comes from variable renewable generation. The obvious observation is that at times there will not be sufficient renewable generation to meet demand and at other times there will be an excess. Overall the results of the modelling indicate that there is a substantial level of excess renewable energy in the system even by 2030. With targets to significantly increase the renewables beyond 2030 this presents an obvious opportunity to use these excess renewables in order to further decarbonise the system. The challenge is of course to find the best ways in which to make use of the excess balancing cost and effectiveness.

3.2 Excess Renewables

Currently in the system excess renewables leads to dispatch down of renewable generation. In general in the Irish system dispatch down of renewables can be due to several reasons which broadly fall into two categories referred to as curtailment and constraint in the Irish system.

- Curtailment is due to system wide issues which may include oversupply, i.e. insufficient demand to absorb all renewable generation or due to system operational constraints which constrain the level of renewable generation to be less than the demand at any time. In Ireland there are four such constraints, a constraint on the maximum level of System Non-Synchronous Penetration (SNSP), a constraint on maximum rate of change of frequency (RoCoF), minimum level of inertia, and a constraint on the minimum number of conventional units online (MUON). This latter constraint is based on fact that conventional generation currently provide a number of essential system services such frequency and voltage stability and system strength.
- Constraint is due to electrical network issues which may be more localised such as congestion and the requirements for network operation within defined standards.

The modelling analysis presented is only considering the curtailment as network constraints are not modelled. Thus the actual level of dispatch down will be higher.

It is worth noting that currently under the terms of the present renewable generation support schemes and single electricity market regulations in Ireland producers are compensated for energy not provide due to curtailment or constraint on the system. Thus the excess renewable energy is actually being paid for which creates an incentive from the system perspective to make use of the energy.

The recent study by Stanley et al.[17] has investigated the impact of implementing various measures on the level of curtailment in the Irish system in a 2030 scenario. In addition to existing measures the study considered the impact of introducing new measures such as medium-duration storage (6 h battery storage), and demand side flexibility from heat pumps, EV charging, flexible operation of data centres and synchronous condensers. Medium duration storage provides the ability to store excess renewables over longer periods of time compared to the typical two hour battery storage currently in use. The demand from certain loads such as EV chargers and heat pumps can be time shifted to a certain extent to provide better coincidence with times of high renewable generation, thus helping reduce curtailment. The study also considered that this may be possible to a certain extent with large industrial loads such as data centres. Synchronous condensers are a technology which can provide voltage and frequency support to the system through the provision of reactive power and inertia respectively. Thus they can supply inertia to the system which would otherwise need to be supplied by retaining conventional generation online (which was the assumption in Figure 3.2. The study considered an optimistic scenario where 60% of EV and heat pump demand and 15% of large energy users had flexibility which accounted for 16% of overall demand in 2030 having a degree of flexibility. The addition of six high inertia synchronous condensers to the system was considered.

In the absence of any additional measures (base case) the study found that curtailment of renewables increased to 21% in 2030. The graph in Figure 3.4 compares the level of total curtailment at each hour of the day with and without the additional measures. Even with all flexibility measures included curtailment remained relatively high at 16%.

The most effective technology, which by itself had the largest impact on curtailment reduction (11% reduction in curtailment) was the use of synchronous condensers. This is due to their ability to provide inertia and hence reduce the level of conventional generation which was required to be online to meet the system inertia constraint. This facilitated meeting more of the demand from renewable generation.

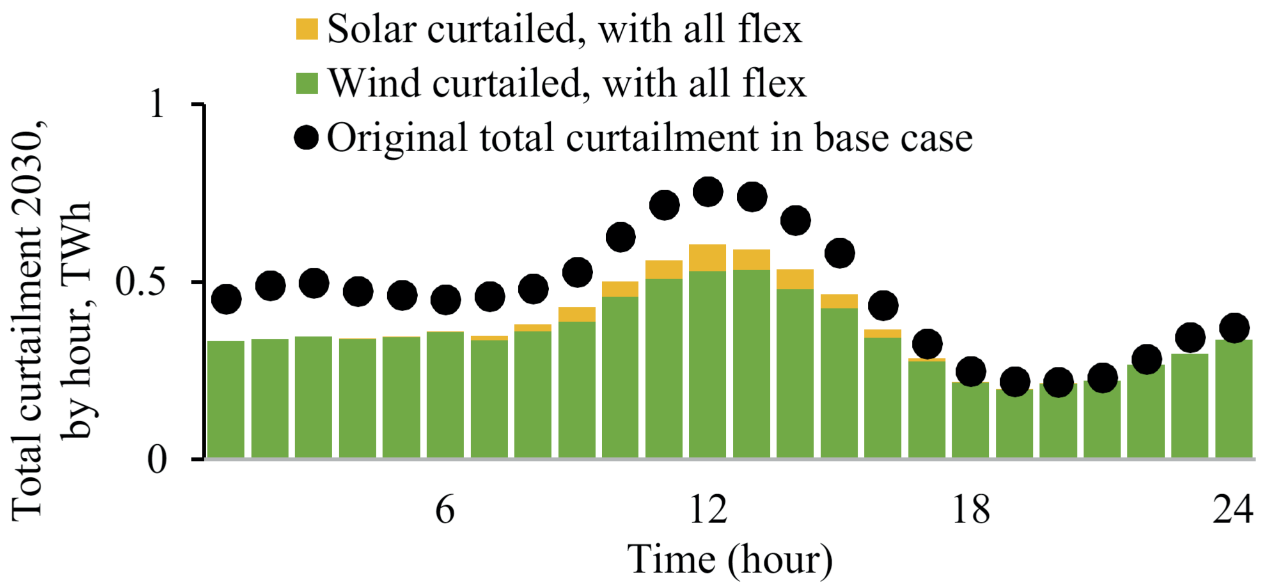

Figure 3.4: Total curtailment in 2030, grouped by hour of the day in the original base case with no additional flexibility measures and with the additional flexibility measures17.© [2023] IEEE

These results suggest that one of the most important constraints in the system from the perspective of limiting increased use of renewables will be the requirement to retain conventional generation because of the services they provide in the system, especially services such as inertia which is linked to system stability. This conclusion is also backed up by a recent study from EirGrid[18] which reviewed the reasons for curtailment in the Irish system based on an analysis of historical data.The analysis showed that the driver for curtailment in the years 2020 and 2021 (accounting for approximately 80% of curtailment) was the need to keep a minimum number of conventional generation units online to ensure system security and stability.

3.3 The 100% Non-Synchronous System

From an emissions perspective the ideal would be to operate the system and supply all demand from renewable generation only, i.e. operating a 100% non-synchronous system. Currently conventional generation provides a number of system services which are essential for the secure and stable operation of the system. Some of the services uniquely supplied by conventional generation at the moment include, establishing the network voltage, provision of inertia, and provision of fault current contributing to system strength. Complete removal of conventional generation in order to achieve emissions reductions would require that these services be provided from other zero-carbon sources. Options being actively pursued include the procurement of low carbon inertia services from technologies such as synchronous condensers.

Another option which has been receiving very significant interest in recent years is the use of grid forming controls for the operation of non-synchronous generation. In the current system all non-synchronous generation (variable renewable generation for wind and PV) is controlled in what is referred to as a grid following manner. Essentially this means that they assume the existence of a grid voltage and based on that their primary function is the delivery of maximum power from the renewable source to the existing grid. They are unable to independently form the grid voltage in the absence of conventional generation. Grid forming implies a change in the controls of the power electronics converters so that the non-synchronous generation or storage can establish the voltage independently and potentially also supply voltage and frequency support, virtual inertia, fault current etc. Pilot demonstrations of grid forming are being carried out internationally and it is becoming clear that grid forming technology is almost certainly set to contribute to the system in the future.

Several studies have investigated the use of grid forming technology in the Irish system. The study by Chen et al.[19] showed that at least in principle the frequency stability of the Irish system could be maintained or even improved under the scenario where all conventional generation was replaced by grid forming converter based generation implemented in battery storage co-located with wind farms.

The replacement of conventional generation by grid forming non-synchronous generation will also have a significant impact on the transient stability of the system during faults. The behaviour of converter based generation depends very much on the control algorithms used to and is also constrained by the strictly limited overload capacity of power electronics converters during grid faults. Another question of interest is how much of the converter based generation should be implemented as grid forming. The study by Zhao et al[20] investigated these issues for the Irish system assuming 100% converter based generation replacing existing conventional generation and the system response to three phase grid faults. The results suggested that in the case that all converter based generation is grid forming, the system is robust against three phase faults irrespective of the type of grid forming control used and the location of the fault. However in practice it is unlikely and may not be necessary for all generation to be grid forming. With the generation connected at individual nodes being either grid forming or grid following the study found that approximately 40% (by capacity) of the generation was required to be grid forming in order to maintain system stability during faults. On the other hand if the generation at each node consisted of a mix of grid forming and grid following the overall required grid forming capacity generation requirement was reduced to approximately 30%. The study notes however that the distribution of grid forming capacity in the system is important and that individual regions may have requirements significantly greater than the system overall average. Moreover the study assumed that the converter based generation was located in the same place the existing conventional generation.

In reality, given Ireland's plans for expansion of offshore and onshore wind the added renewable generation is likely to be located where the wind resource is greatest. In a further study Zhao and Flynn[21] extended their previous work taking into account locations for the converter generation which were more remote from the load centres and more representative of where future wind generation resources are likely to be located. Considering also some important enhancements to the converter controls the system was found to be stable with a minimum of approximately 30% grid forming capacity in this more "remote" generation scenario.

Clearly grid forming technology will have an important role to play in the system in the future as it providing a replacement for conventional generation and hence a route to increase generation from renewable sources. Although demonstration projects and trials of grid forming are ongoing there is no experience of the operation at scale. Since the dynamics of converter based generation are fundamentally different from conventional generation and are entirely dependent on the control algorithms there are considerable unknowns related to their interaction with other assets in a large scale realistic system. Thus there are still significant questions to be addressed around issues related to dynamic interactions, provision of system strength and fault current, and provision of frequency and voltage support before the 100% non-synchronous system can be implemented.

In summary the technical challenge of lies in the balancing of supply and demand over different time ranges from sub-seconds to years. Sub-second balancing requires a sufficient level of fast acting resources which can also provide services related to system stability such as inertia, voltage support, frequency support, system strength many of which are currently supplied by conventional generation. Battery storage and various demand side flexibility measures provide likely sources of balancing over the time scale of hours. Balancing over longer durations of days to years requires the implementation of forms of long duration storage. Recent work by NexSys researchers related to sources of flexibility in the system and their impact in the system are discussed further in the next section.

4. Review of Nexsys Research

In this section we present a brief review of published research work from NexSys researchers which is of relevance to charting the future Irish Energy System. Research works mentioned are selected based on their direct relevance to the Irish system and/or use of the Irish system as a case study and on the relevance to charting future pathways. The research is described under several topics which are generally considered as important aspects of a future decarbonised energy system. These topics are: sources of flexibility in power system, the role of hydrogen and aspects relating to uptake of low carbon technologies.

4.1 Sources of Flexibility in the System

In general flexibility in the system can be provided by centralised assets such as storage or flexible generation or from distributed demand side assets such as industrial demand, building demand, or EV charging. Different sources can help with system balancing over different times scales, with some sources being suitable for short duration fast acting flexibility and others suitable for slower and longer duration flexibility.

The study by Yasuda et al.[22] conducted under the International Energy Agency Wind Task 25 framework, explores and evaluates power system flexibility across multiple countries such as Japan, North America, Australia, and Europe utilizing an accessible "Flexibility Chart 2.0" to estimate and compare the potential of flexibility resources. Flexibility resources considered are (i) interconnection, (ii) Combined Heat and Power (CHP), gas turbines (CCGT and OCGT), (iv) hydropower based on reservoirs, (v) pumped hydro. The information is compiled from available statistical data in several countries and for this reason demand side flexibility is not included due to a lack of data. Battery storage has been proposed for inclusion although only limited data is yet available. As an example Figure 4.1 shows the historical trend in the development of flexible resources in Ireland, also projected to 2030, including the battery storage axis. For an international comparison Figure 4.2 shows similar graphs for South Australia, which is another system with very high renewable penetration levels. It is notable in both cases that gas turbines are set to remain the largest source of flexibility in the system in the frame of 2030. However there is a very significant anticipated growth in flexibility from interconnection and battery storage.

The work allows the comparison of flexibility resources in a very wide range of countries in an easy to understand, high level manner. It also enables comparison of past, current, and future flexibility resources, aiding energy policy discussions and consensus-building, particularly in regions transitioning to renewables. It is recognised however that the Flexibility chart has the limitation of not providing any information on the time scale of the flexibility, i.e short term (seconds to minutes), medium term (hours to days), or long term (weeks to seasons). Moreover as it is based on actual existing data it does not yet capture the future potential of newer resources in the provision of flexibility.

The study by Kiviluoma et al.[23] examines the potential of flexibility from other resources such as electrification of heating, transport and industries in support of a 100% Sustainable System. It highlights that different forms of storage are key potential sources of flexibility over different time scales and some of these and their associated times scales are shown in Figure 4.3. The capital costs of different storage technologies have also been estimated as shown in Figure 4.4 which indicates that battery storage is among the more expensive forms.

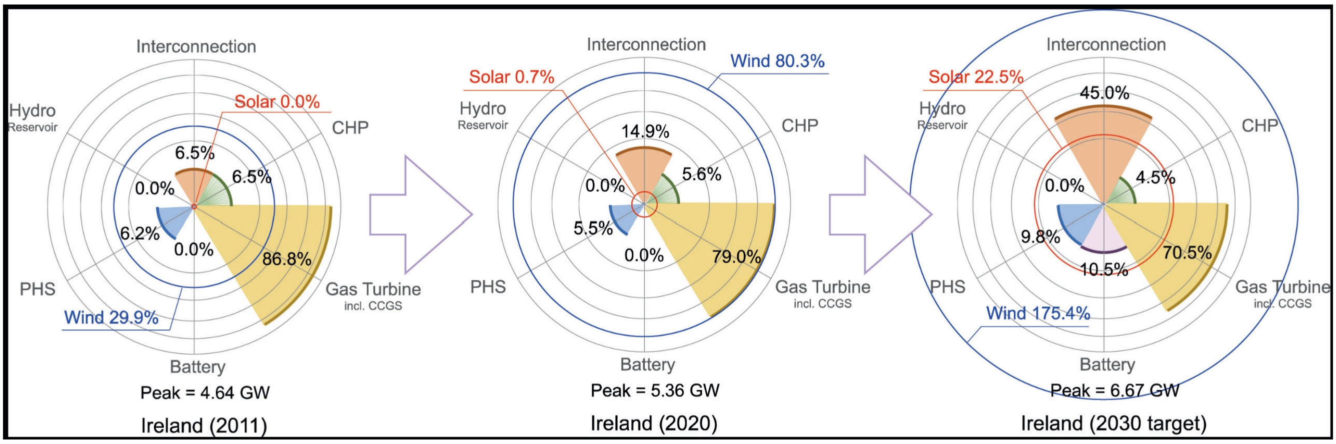

Figure 4.1: Historical change in the flexibility resources in Ireland using the flexibility chart tool[22].

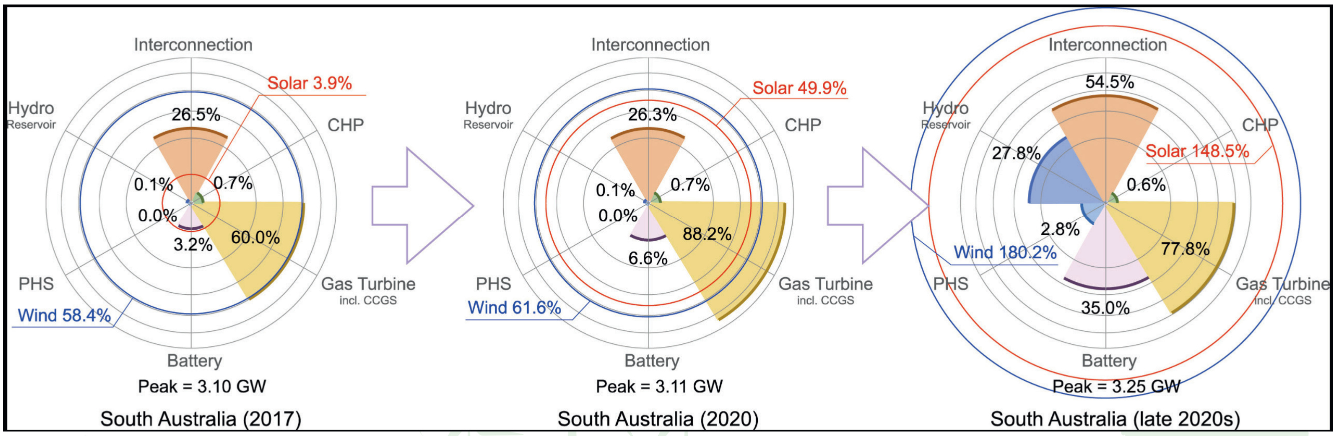

Figure 4.2: Historical change in the flexibility resources in South Australia using the flexibility chart tool[22].

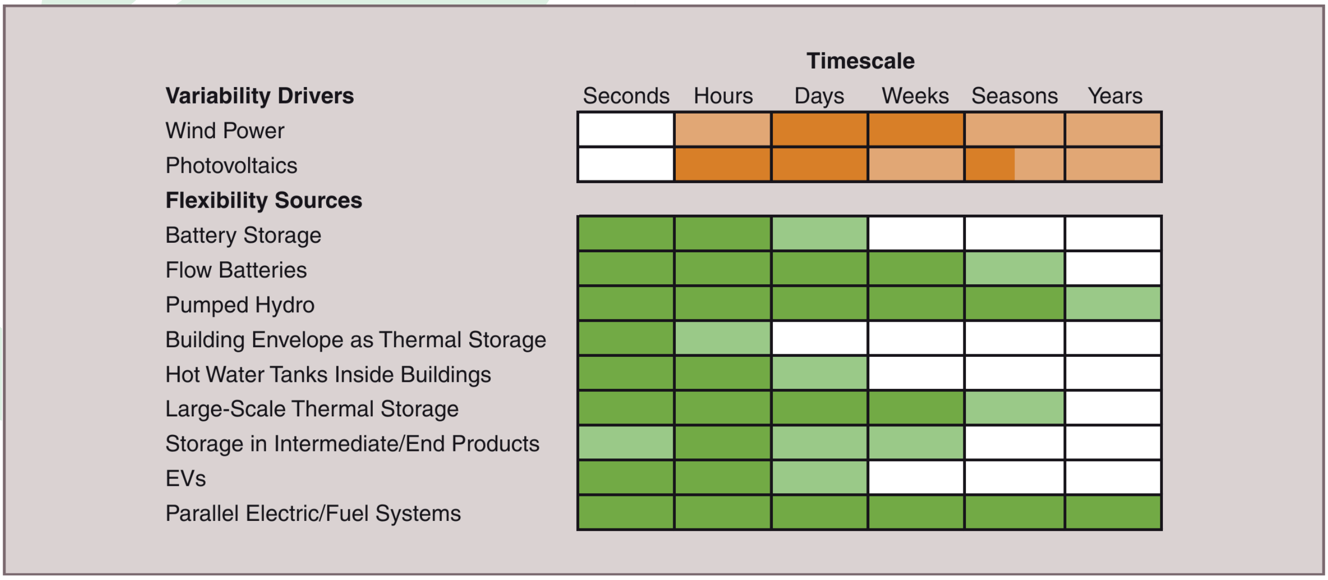

Figure 4.3: Estimated time scales for the drivers of variability in the system and sources of flexibility - darker colour: primary impact, lighter colour:secondary impact, white: not usually relevant (taken from 23) © [2023] IEEE.

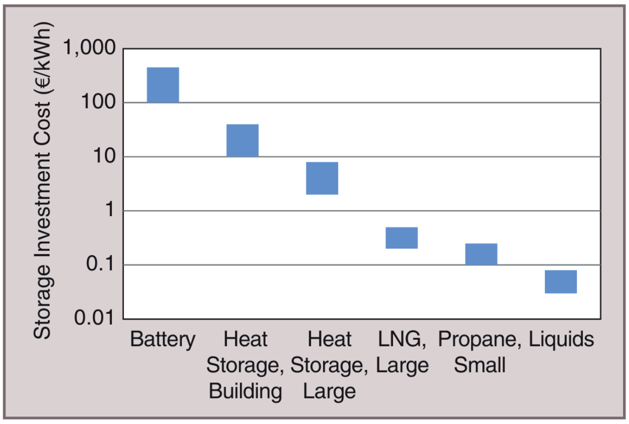

Figure 4.4: Estimated investment costs for different forms of storage (taken from 23) © [2023] IEEE

However harnessing flexibility and storage from buildings for example faces the challenge that the benefit for any one building owner may be quite small. Similarly there can be considerable flexibility in EV charging, but incentivising owners to participate may be challenging considering the benefits for a single EV owner are small. The work concludes that although electrification of the heating, transport and to some extent industrial systems seems inevitable, it is by no means guaranteed that such electrification will also provide the needed flexibility. Ensuring this requires appropriate policies, legislation, and market regulation as well as participation from energy consumers. The work concludes *"There will always be an interplay between 1) legislation, which needs to enable efficient solutions; 2) market mechanisms, which need to remunerate for all kinds of valued services; and 3) standardization, user-friendly technologies, contracting, and the means to conveniently aggregate small loads, which can help facilitate consumer-level adoption."*

The studies by Kiviluoma et al.[24] and by Stanley et al.[17] have taken a closer look at the impact of implementing various new potential flexibility resources in the Irish system. Kiviluoma et al.[24] focuses on the impact of various flexibility measures on the integration of renewable energy in the power system of Ireland. Measures considered include hybrid heating in domestic and industrial processes, smart charging of electric vehicles, renewable hydrogen, power to ammonia, peak shaving demand response, and batteries. The analysis was performed using the energy systems modelling tool Backbone, which uses multi-sectoral analysis and detailed power system representation. The study quantifies the interactions and dependencies between different flexibility measures and compares the scenarios in terms of their influence on system inertia, renewable energy curtailment, and non-synchronous penetration levels. The results indicate the potential importance of electricity-based heating in the industrial sector, smart charging of electric vehicles, batteries, and power-to-ammonia in achieving future targets.

Stanley et al.[17] further studied strategies for enhancing grid flexibility in Ireland under the projected target of 80% of electrical demand being supplied from wind and solar by 2030. Importantly the study uses a methodology which addresses stability issues such as rate of change of frequency (RoCoF) constraints, minimum inertia levels and SNSP constraints. Neglecting such stability issues can lead to unrealistic operational scenarios. In addition to the more conventional sources of flexibility such as interconnection, PHS, and gas plant, the study also considers the use of synchronous condensers, medium-duration storage (6 h battery storage), and demand side flexibility from heat pumps, EV charging, and flexible operation of data centres. The study concluded that all flexibility measures taken together resulted in an 11% reduction in system operational costs (in 2030) by decreasing dependence on conventional plants for inertia and peak energy needs. The study also focussed on the reduction of curtailed renewable generation achievable from the various flexibility measures, which was projected to be 21% in 2030 in the absence of extra flexibility measures. Even with all flexibility measures included curtailment remained relatively high at 16%. Interestingly the flexibility measure with the largest impact on curtailment reduction (11% reduction in curtailment) was the use of synchronous condensers, which displaced the requirement for conventional generation to meet RoCoF and inertia constraints.

Data centres represent a growing load on the system, with EirGrid predictions that they could account for up to 30% of demand by 2030. Flexibility in data centre demand is therefore a topic of some interest. The study by Misaghian et al.[25] investigates operational flexibility in data centres using machine learning algorithms based on synthetic datasets to predict energy consumption and server temperatures. Flexible operation was assumed to be achieved from a mix of IT workload rescheduling considering flexible and inflexible workloads, cooling equipment consumption adjustment and use of on-site battery back-up. The models were applied to a system-wide fleet of data centres, integrating with a power system scheduling framework which enabled demand shifting based on carbon intensity. Five flexibility scenarios were compared, showing the potential for a 6.5% load reduction during high CO_2 intensity periods over the course of one winter day operation.

Misaghian et al.[26] further explores flexibility from the commercial sector with a specific focus on the use of supermarket refrigeration systems as fast frequency response (FFR) resources. The study estimated that 2.5% of total electricity demand could be associated with supermarket refrigeration systems amounting to a mid-summer system load of approximately 140 MW. The study considered the impact on system frequency response resulting from loss of largest infeed to the system for the Irish power system in 2030. Results indicate that utilizing refrigeration as DR units for FFR can lower total production costs and enhance frequency stability after a generation loss. Simulations over a year underscore the importance of FFR volume in mitigating frequency transients, reducing the probability of extreme rate of change of frequency (RoCoF) events by 90% and low frequency nadirs by 77% with the inclusion of FFR from refrigeration systems.

Buildings consume approximately 36% of global energy production and consequently present an important target for decarbonisation measures. Moreover the energy consumption of buildings has significant potential for flexibility, especially so as electrification of heating and transport progress. However understanding the degree of flexibility in diverse buildings and quantifying that flexibility can be challenging. In this context data driven methods[27,28,29] based on analysis of real data sets are seen as a promising way to quantify building flexibility and derive appropriate key perfromance indicators.

The study by Li et al.[28] (conducted as part of IEA Annex 81) provides a review of such data-driven methods for quantifying building energy flexibility, categorizing existing energy flexibility key performance indicators (KPIs), analyzing public datasets for energy flexibility studies, and identifying research trends and future opportunities in the field. The study by Bampoulas et al.[29] further shows how machine learning approaches can be used to address the challenge of quantifying and characterizing the flexibility of individual residential buildings without relying on complex simulation models. It proposes an ensemble learning framework based on four different machine learning models. Day-ahead and hour-ahead prediction models are developed and periodically updated based on residential occupancy patterns. The results show that the ensemble models developed for each target variable outperform each of the constituent machine-learning algorithms. The modelling is applied to a case study on a single story detached building in Ireland which included a heat pump, a photovoltaic system, and a battery unit and considered two different occupancy profiles. This framework can aid electricity aggregators in evaluating building portfolios or optimizing energy flexibility for shifting electricity usage to off-peak or excess onsite renewable energy generation periods.

Accurate modelling of building energy usage also requires consideration of occupancy patterns. Sood et al.[30] proposes a novel approach for modelling occupancy patterns in buildings using data from the Time Use Survey (TUS). Energy simulations were conducted to assess the impact of these realistic occupancy schedules on residential buildings at various spatial scales. Results indicated significant variations in annual energy demand (8%–10%), monthly heating (25%), and electricity consumption (32%) compared to conventional schedules. Daily variations in heating and electricity consumption were reported as 50% and 12%, respectively. Incorporating realistic occupancy schedules in building archetypes is crucial for accurate energy predictions and informing policymakers and planners for effective energy strategies.

Flexibility is a term which can encompass changing energy usage over different times scales and over different geographic scope. However if the flexibility comes from demand side resources which are ultimately connected to the distribution network then consideration should be given to their operation in a manner which doesn't conflict with local network management standards. For flexibility services provided to the overall system this requires some form of interaction and co-ordination between Transmission System Operators and Distribution System Operators. In this regard, the study by Rabiee at al[31] presents a model which addresses interactions between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) in scheduling Distributed Energy Resources (DERs) such as Electric Vehicles (EVs) and Photovoltaics (PVs). It optimizes EV schedules to maintain energy delivery in the Medium Voltage (MV) network while ensuring the Available Transfer Capability (ATC) in the High Voltage (HV) network. Coordination of On-Load Tap Changer (OLTC) settings at the TSO-DSO boundary is integrated with DER scheduling. The model considers uncertainty in PV generation, EV behaviour, and network demand through scenario-based stochastic optimization. Results show that TSO concerns influence EV charging demand, OLTC voltage set-points impact network capacity, reactive power support enhances EV supply capability, and considering upstream network variability and DER/demand uncertainty reduces network constraints.

4.2 The Role of Hydrogen

The interest in the use of green hydrogen for storage and as an energy carrier in the energy system has grown rapidly in recent years. In Ireland for example the CAP 2024 envisages 2 GW of green hydrogen production from offshore wind in the 2031-2035 time frame. The national hydrogen strategy8 envisages the development of a green hydrogen sector in Ireland with the aims of aiding in decarbonisation of the economy and enhancing energy security while also creating industrial and export market opportunities. Initial developments pre-2030 envisages the use of excess renewables for the production of green hydrogen with production from future offshore wind generation envisaged in the 2033 to 2050 time scale. However for green hydrogen production to become economically feasible there should be demand for such a product. Although by far the largest demand for hydrogen globally is currently in heavy industrial uses, there is growing interest in energy system uses.

However the end uses for green hydrogen requires careful consideration as there can be very considerable efficiency reductions. For example the 2018 study by Transport & Environment on the decarbonisation of European cars compared the overall efficiency of different means of decarbonising road transport, concluding that direct electrification had a 77% efficiency, the use of green hydrogen had a 30% efficiency and power to liquid a 13% efficiency.

The study by Laguipo et al.[33] explores the potential for the heavy duty transport sector in Ireland as a market for green hydrogen considering that Ireland lacks a heavy industry market. The study investigated the interest from the heavy duty transport sector via a survey and also quantified the potential annual hydrogen demand and the delivery costs. Cost models show feasibility, with potential for a nationwide refuelling infrastructure as demand grows.

The study by Ekhtiari et al.[34] explores the impact of blending green hydrogen into the gas network. This study, focusing on the Irish gas network, explores how injecting 11.6% hydrogen content impacts gas network operational variables such as pressure and flow rates. Results show a 12% rise in pressure drop and a 15% increase in flow rate, which are considered to be within acceptable limits. Additionally, there's a potential 2% reduction in natural gas requirements, cutting daily natural gas usage by 200,000 Sm3 and reducing CO2 emissions by 432 metric tonnes on a specific day.

Gholamian et al[35] explores the feasibility of using hydrogen injection into biogas from anaerobic digestion to power a wastewater treatment plant. For this study a Polymer electrolyte membrane electrolyser fuelled by Photovoltaic panels produces hydrogen, which is then used in micro gas turbines for electricity generation. Transient modelling shows that hydrogen injection reduces CO2 emissions for the site by up to 30%, with two micro gas turbines producing over 265 kW of power. The Levelized Cost of Hydrogen (LCOH) is estimated to be $8.3/kg H2, with a payback time of 6.5 years. The system can generate 70-400 KWe of electrical power and 120-500 KWth of thermal energy annually, with efficiencies reaching 37.5% for power generation, 83% for Combined Heat and Power (CHP), and 78% overall.

The study by O'Dwyer et al[36] takes a system wide view for Ireland and explores optimal investments in Hydrogen generation and storage within Ireland's renewable-heavy All-Island power system in the time frame of 2030 and 2040. Using an investment planning methodology, the study investigated the optimal investment (for minimum system cost) in various hydrogen technologies (Hydrogen storage, generation using hydrogen OCGT, Hydrogen CAES) under different future energy scenarios and making assumptions regarding projections for technology costs and hydrogen demand. In 2030, investments in electrolysers are shown to be quite low due to the high technology cost and limited green hydrogen demand. Investments do occur in specific scenarios which assume considerably reduced costs or significantly increased hydrogen demand. However, by 2040, significant investments occur across all scenarios, particularly when Hydrogen demand is high. The study suggest a lowest case scenario investment of 5 GW electrolyser capacity in 2040.

4.3 Technology Uptake & the Role of the Energy Citizen

Citizen engagement and achieving a just transition are important pillars of the Climate Action Plan. Many of the targeted measures related to the electrification of transport and heating and increasing microgeneration depend on public uptake of the technologies. Several works by NexSys academics have investigated issues related to the public uptake of such technologies.

The study by Nouri et al.[37] has reviewed some of the regulatory challenges hindering European citizens' sustainable engagement in the energy transition. It identifies barriers in regulations, standards, and network codes obstructing efficiency measures, demand response, and local energy markets. Utilizing a four-step methodology, it includes literature review, enabler identification, barrier filtering, and barrier impact assessment across EU states. Case studies, like trials in Ireland, demonstrate insights for updating network codes. The paper stresses the importance of integrating citizens as flexible energy sources, underscoring the need to address regulatory gaps. Ultimately, it emphasizes developing effective standards and regulations for successful citizen integration, providing valuable insights and recommendations for EU member states.

Apart from regulatory issues, it is clear that people's attitudes and perceptions are important in understanding the potential for technology uptake. The study by Meles et al.[38] is aimed at understanding Irish household preferences for new home heating alternatives, such as heat pump systems. To do so it analyses survey data from a nationally representative sample of 1208 Irish individuals, along with conducting a discrete choice experiment involving 408 respondents. Some of the findings of the survey are shown in Figure 4.5 above. Findings reveal that approximately 60% of the population holds positive views toward heat pumps,

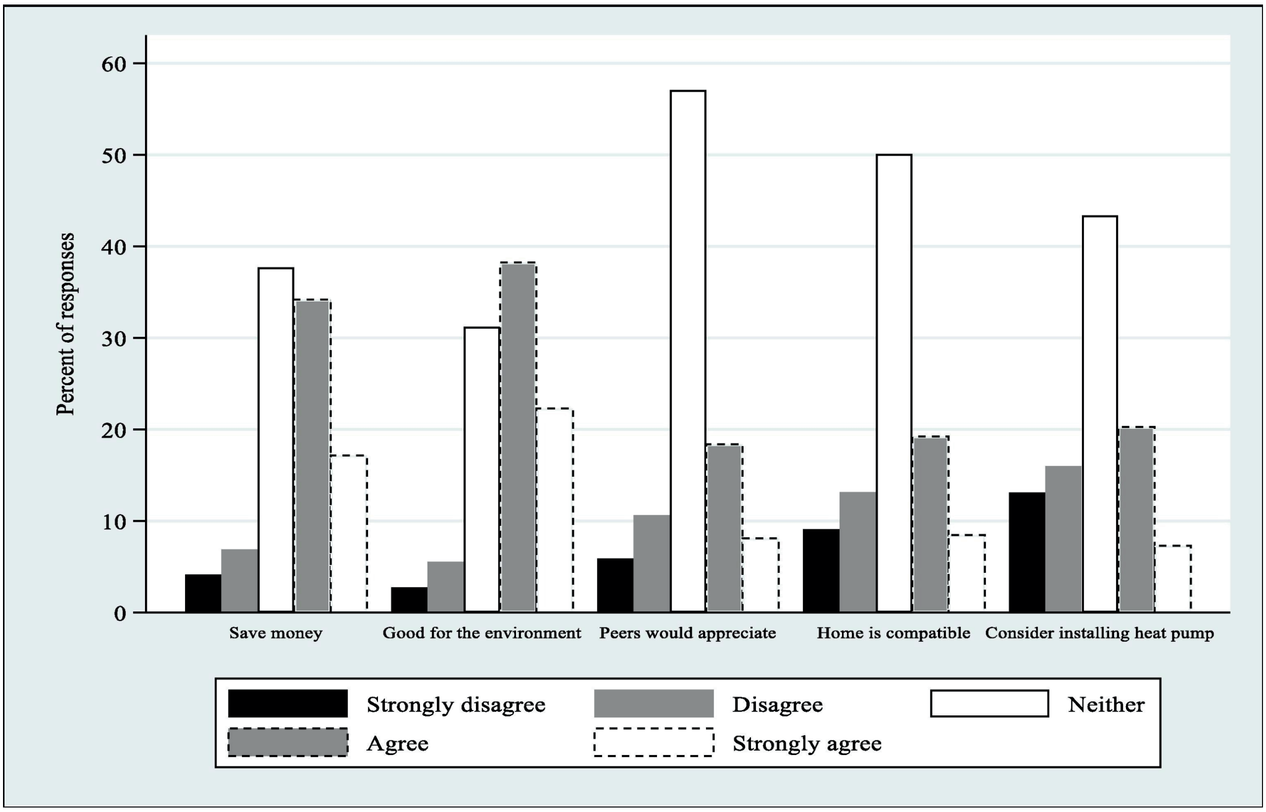

Figure 4.5: Distribution of responses to psychological construct statements used to measure attitude, perceived behavioural control and intention to install a heatpump[38].

while around 17% are against them and 22% are neutral. The discrete choice experiment reveals that factors beyond financial considerations, such as installation inconvenience, environmental sustainability, and improved home comfort, significantly impact the likelihood of adopting new home heating systems like heat pumps. The findings demonstrate diverse preferences among households. Irish households are willing to invest in ground source heat pumps despite high upfront costs. Positive views toward heat pumps, driven by energy savings and environmental concerns, increase adoption likelihood. However the inconvenience associated with installation remains a concern. Tailored measures could target different groups. The findings support environmental benefits and comfort as crucial factors in heating system choices.

conditions, the model projects approximately 260,000 heat pumps to be installed in existing Irish homes by 2030, constituting around 15% of the country's households. Sensitivity analyses reveal the impact of various factors such as upfront costs, grant amounts, and energy prices on adoption rates. The study identifies factors influencing heat pump adoption in Irish households and highlights significant energy savings and emissions reductions. However, it acknowledges limitations and offers insights relevant beyond Ireland for sustainable energy transitions.

The existence of charging infrastructure and charging services are a considerable influencing factor on the uptake of electric vehicles and hence in the achievement of transport electrification targets. The study by LaMonaca and Ryan[40] reviews the state of play in electric vehicle charging

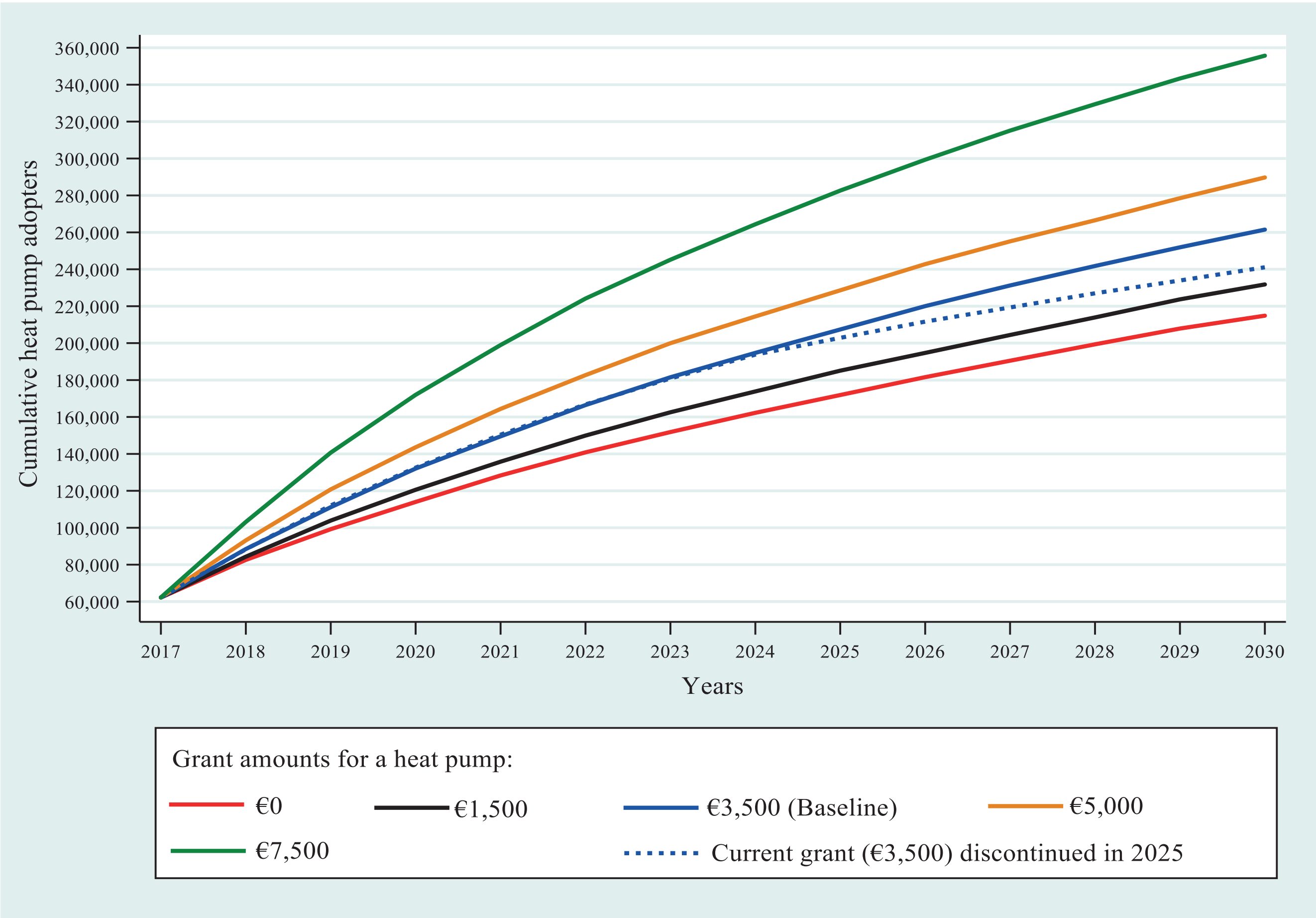

Figure 4.6 Uptake of heat pumps to 2030 simulated over different grant amounts (Meles and Ryan, 2022)

The study by Meles and Ryan[39] continues this vein of research by using an agent-based model to understand how Irish households decide to adopt heat pumps. The model considers psychological and social factors, not just economic ones, using data from a national household survey to create realistic simulations of decision-making. Under current

services globally in 2022. The work reviews charging services and infrastructure from the perspectives of types of charging, charging infrastructure market (including business models, stakeholders, industry lesson learned, economics of charging infrastructure) and incentives and deployment approaches (including instruments to support investment and network impact). Based on the review the study draws some policy recommendations summarised as follows:

- Improve transparency for customers regarding pricing in commercial charging services, e.g. Standardize pricing structures (per-minute, per-hour, per-kWh, subscriptions), consumer protection laws and standardised labelling for easy comparison.
- The build out of charging infrastructure requires continued support though publicly funded subsidies and public-private partnerships.
- Data on public charging usage should be more publicly available in order that researchers and policy makers can conduct analysis around network usage to help with planning and siting of infrastructure.
- Using models to predict the uptake of technology is important for planning purposes.

The ability to successfully complete larger scale renewable energy projects on time can be quite dependent on public acceptance of such projects. Addressing this aspect the study by Meugorac and G. Schuitema[41] explores the role that governance approaches plays in community acceptance of renewable energy projects. It demonstrates, though the use of surveys carried out in the Irish midlands that communities are more likely to accept renewable energy developments which are based on bottom-up governance approaches. This contributes to stronger collective psychological ownership and better place-technology fit, compared to those based on top-down approaches. To enhance community acceptance, energy projects should focus on community-driven, bottom-up governance, involving community participation in decision-making processes.

The concept of a just transition is often mentioned in relation to the minimisation of social injustices associated with the energy transition. The study by Banerjee and Schuitema[42] highlights how the concept of a just transition, aimed at safeguarding vulnerable groups during energy transitions, faces challenges in practice, as is evident from a case study in the Irish Midlands arising from the shutdown of peat-based electricity generation in 2020. Despite stakeholder consensus on the importance of protection, a disconnect between theory and implementation has led to frustration and distrust, particularly among the peat workers. The Irish Midlands case underscores the need for a clear, independent-led just transition process involving all stakeholders to bridge the gap between theory and practice. Without adhering to distributive, procedural, and restorative justice principles, neglecting this approach risks stalling energy transition efforts and eroding public support for renewable energy and climate policies. Importantly the study elaborates on how such a process should be structured so as to provide benefits to all.

5. Future Directions

The general direction of pathways towards a net zero energy system and consensus on the main features of such a system are emerging, as discussed in Section 2.1. The 2030 sectoral targets which represent major milestones on the pathway are also now well-defined. Nevertheless, at the present moment progress is behind where it needs to be in order to meet the targets. There is still also a massive leap to go from the interim 2030 targets to the net-zero system goal in 2050 with many uncertainties in how pathways might develop in the 2030 to 2050 timeframe. Uncertainties relate to the technical and economic characteristics of technologies, the financing of new technologies and their acceptance and uptake by the population.

Although there is growing consensus on the broad set of technologies needed, there are significant questions remaining around which new technologies might emerge and what the development trajectory, both technically and economically, might be for of currently immature technologies? In addition very significant levels of investment in new and existing technologies is required to actually implement the transition and there is great uncertainty around how this investment is incentivised. Clearly public investment is needed to support immature, emergent technologies that are currently non-commercial but can contribute to realising future climate goals at lowest cost in the public good. The ongoing objective of the roadmapping exercise in NexSys is to explore the technical and economic impact of different technology portfolios to achieve the net zero system goals under different scenario assumptions.

5.1 Storage and Maximising the Use of Renewables

Increased electrification with very significant expansion of generation from renewable energy sources (RES) is without a doubt a key strategy underpinning all decarbonisation pathways. A primary focus of the future NexSys research is to explore the ways to make maximum use of variable renewable generation. By 2030 it is clear that considerable excess renewable energy will exist at times of high RES generation. There is an obvious opportunity to make use of these through increased storage capable of storing energy over different time durations, particulary with longer duration than the currently used battery storage. Therefore, exploring the options for longer duration storage are becoming important, with technology options such as flow batteries, compressed air, and storage as gas through power to gas among some of the options to be explored. The latter is of particular interest for long duration storage and security of supply, in terms of storing energy from high RES periods for use in times when there may be extended periods of low renewable generation.

5.2 Quantifying the Impact of Res Droughts

In a system which is highly dependent on variable renewable generation, extended periods of low renewable resource, i.e. RES droughts, become a particular concern for security of supply. The frequency and duration of such RES droughts has important consequences for the capacity of storage required in the system. Ongoing work in NexSys is focussing on quantifying these RES drought periods from historical weather data and also projecting how they might change in the future with climate change. An important aspect of this work will be to assess the implications for the sizing of long duration storage in the system to cover worst case weather scenarios.

5.3 Quantifying System Flexibility

The balancing of supply and demand in the context of a 100% renewable system can be facilitated by achieving increased flexibility from the demand side. A key question of interest is which flexibility sources provide the highest benefit-cost ratios for the provision of flexibility at different time scales. Its most likely the case that the system will benefit from a range of different sources both centralised and distributed. Flexibility sources of particular interest are the transport sector, as electrification progresses, and the buildings sector, as microgeneration and electrification of heating progresses. Quantifying the flexibility available from different resources and its impact in the system will remain a key focus area for NexSys research.

In the transport sector, for example, it is clear that there is consider potential for flexibility associated with the electrification of road transport. This can be leveraged through the use of flexible charging in order to shift charging demand to times of lower system demand or higher renewable generation. Beyond flexible charging, the introduction of Bi-directional charging of electric vehicles to facilitate vehicle to X (where X could be grid/home/building etc.) introduces further possibilities for increasing flexibility. The considerable quantity of stored energy in EV batteries could be used to advantage to support the grid in various ways through the provision of system support services (V2G). Additionally, technology such as Vehicle to Home (V2H) presents opportunities for EV owners to reduce their overall energy bills through the use of their EV battery as a form of storage. This technology also provides added incentives for the adoption of EVs. The quantification of the benefits of V2G or V2H technologies for the overall system and for individual EV owners is a focus area in ongoing NexSys research.

5.4 Low Carbon Technology Adoption

An important underlying assumption in decarbonisation pathways is the adoption of low carbon technologies such as heat pumps and EV by people. But this adoption and especially the high rate of adoption required to meet 2030 targets is by no means guaranteed. Therefore, gaining an understanding of people's attitudes to such technologies and hence an understanding of the barriers and potential incentives necessary to overcome those barriers is important. The modelling of adoption rates by means of models calibrated by survey data collected from households is ongoing work which will form the basis for including informed technology adoption rates in the development of scenarios. Furthermore, how people use the technologies and whether their pattern of electricity use changes with increased electrification and heat is important to understand the implications for future electricity system demand and potential for flexibility provision.

5.5 Accommodation of Offshore Wind

Significant expansion of offshore wind is a critical part of the decarbonisation strategy for the Irish system. The medium-term development of offshore wind is well underway with for example the approximately 3 GW capacity awarded under the ORESS auction schemes. The strategy documents on the development of offshore wind envisage the potential for much larger capacities post 2030. However, the utilisation routes for such large quantities of offshore wind have considerable uncertainty. The potential resource is more than the electrical energy needs of the country, which means that the development of other products and routes to market for the excess resource become important. Options for the utilisation of the generated electricity, including offshore grids, interconnection, integration with hydrogen and gas systems and its use in the transport sector, are being explored in ongoing NexSys work. For example, the potential for accommodation of offshore wind, considering an interlinkage with the gas system through the use of power to gas and the potential use of green hydrogen in the gas network, is currently being investigated.

5.6 Green Hydrogen Demand

Very much linked to this is the need to quantify the demand for green hydrogen from all potential sectors including direct industrial employment and use in transport and industrial heating. The national hydrogen strategy places an emphasis on the development of an indigenous hydrogen market. The use of green hydrogen in the transport sector as a fuel source in heavy goods vehicles (HGV) may be of particular importance considering that viable options for decarbonisation of freight transport beyond direct electrification are likely to be required. Ongoing research in NexSys is exploring the opportunities and barriers to establishing a market for green hydrogen. Discounted cashflow analysis finds that using offshore wind for the production of renewable hydrogen is not currently commercially feasible and there are a large number of uncertainties to be resolved. NexSys researchers in finance, climate, and energy systems are working to identify the feasibility of one potential route to market where Ireland may have a competitive advantage- sustainable aviation fuels (SAF), which are critical for achieving the carbon emission reductions necessary in the aviation sector.

Further roadmapping activities will include deeper investigation of the above topics leading to the development of scenarios or pathways to a decarbonised system informed by the detailed research being done by NexSys researchers across the five strands of the programme.

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