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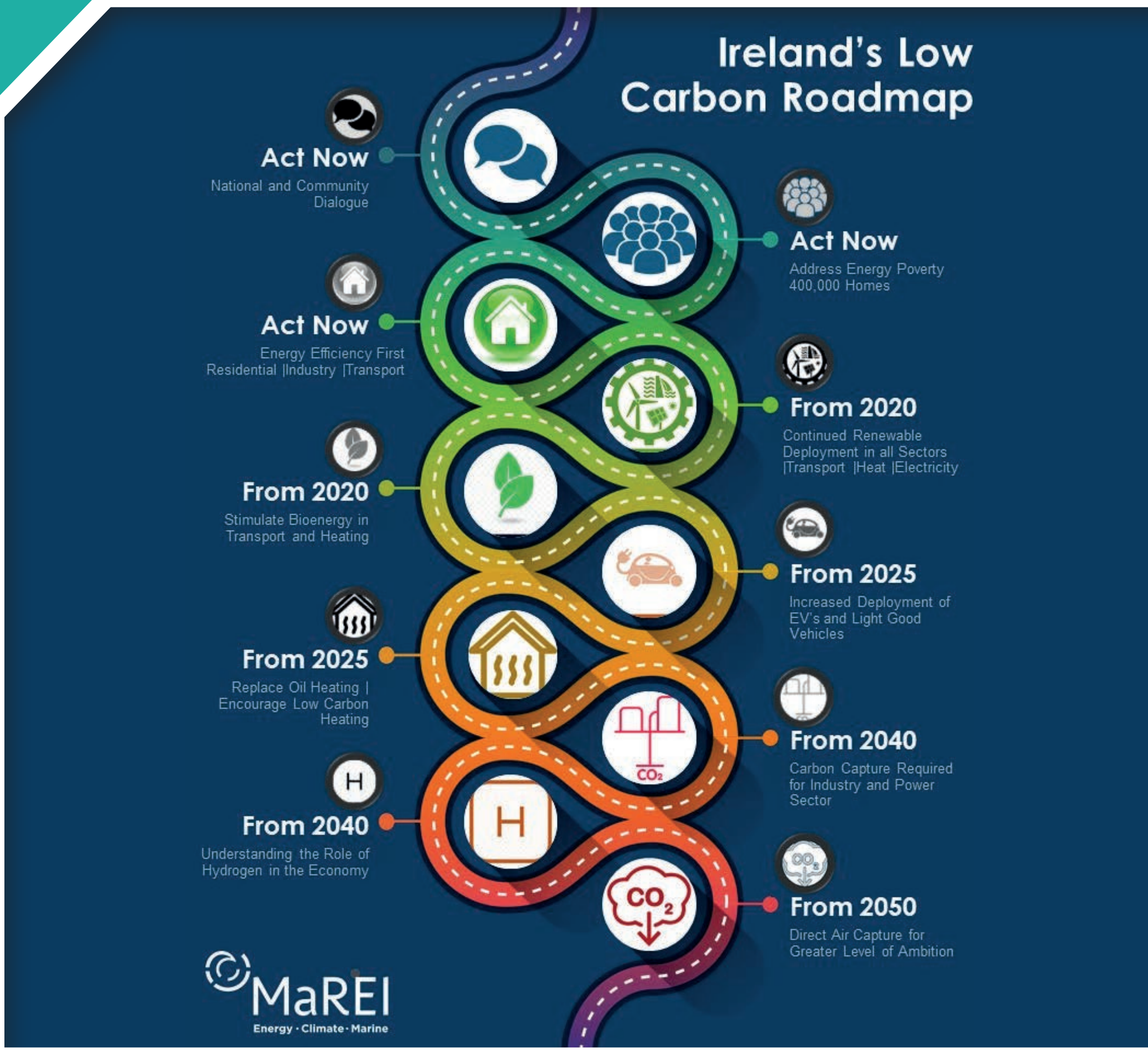
The Role of Energy Technology in Climate Mitigation in Ireland: Irish TIMES Phase 3

Authors: Brian Ó Gallachóir, Paul Deane, James Glynn, Fionn Rogan



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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

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The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

The Role of Energy Technology in Climate Mitigation in Ireland: Irish TIMES Phase 3

(2013-CCRP-MS.13)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Science Foundation Ireland MaREI Research Centre for Energy, Climate and Marine, Environmental Research Institute, University College Cork

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This report is based on research carried out/data from January 2014 to October 2017. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The warming of our climate system is unequivocal and many of the observed changes in temperature, weather systems and oceans are unprecedented over decades to millennia. Human activities such as the unabated burning of fossil fuels, changing land use patterns and inefficient agriculture practices are driving these changes.

In 2014, the Irish government adopted a National Policy Position for an 80% reduction in CO_2 equivalent emissions by 2050 compared with 1990 levels for the electricity generation, built environment and transport sectors. The policy position also sets out an ambition for carbon neutrality in the agriculture and land use sector, including forestry, which does not compromise on national capacity for sustainable food production. More recently, the government's Climate Action Plan set out a pathway to 2030 to meet European emissions reduction targets, and the Irish government has broadly supported the adoption of a net zero target for the European Union (EU) as a whole by 2050.

Irish TIMES Phase 3

The Irish TIMES (The Integrated MARKAL-EFOM System) Phase 3 project evaluates the role of energy technology in climate mitigation in Ireland, noting that technology is just one dimension of addressing climate change, along with adaptation and behaviour change. The Environmental Protection Agency and the Sustainable Energy Authority of Ireland have funded the development of the Irish TIMES energy systems model since 2009. This project covers the period from November 2013 to October 2017 and enabled the Science Foundation Ireland MaREI Research Centre for Energy, Climate and Marine to further develop Irish TIMES, Ireland's only fully integrated long-term energy systems optimisation model, and to build further research capacity in energy systems modelling. The key methodological developments achieved in this project were:

- the inclusion of negative emissions technologies in Irish TIMES, enabling MaREI to build net zero emissions scenarios for Ireland that are consistent with the Paris Agreement;
- enabling Irish energy modelling researchers to take a leadership role in developing the EU PLEXOS electricity systems model and the global TIMES Integrated Assessment Model.

Contributions to Policy

The effective use of technologies on both the demand and the supply sides of the energy system can enhance the decarbonisation process, reduce overall societal costs and deliver broader benefits, such as enhanced security of supply and greater system resilience. These pathways also require an enabling policy environment, access to finance and technology maturity.

This project contributed directly to improving energy and climate action policy development in Ireland. The research capacity in MaREI's Energy Policy and Modelling team was effectively utilised to inform key policy developments, including:

- supporting the Irish government in negotiating with the European Commission in 2014 – the outcome was agreement on Ireland's target of a 30% reduction in non-Emissions Trading System greenhouse gas (GHG) emissions by 2030 relative to 2005 levels;
- building scenario analysis on decarbonising energy, energy security and addressing energy poverty to support the Department of Communications, Energy and Natural Resources during the summer of 2015 – the outcome was the White Paper on Energy, *Ireland's Transition to a Low Carbon Energy Future 2015–2030*, published in December 2015;
- scenario analysis to inform the government's first National Mitigation Plan in 2017 – this analysis focused on how to meet Ireland's mandatory target under EU legislation for GHG emissions reduction by 2030;
- analysing the impacts of increasing Ireland's long-term ambition to 2050 beyond the 80% CO_2 emissions reduction target – this informed the government's Climate Action Plan in 2019.

Recommendations

This report focuses on the role of clean technologies in all sectors of the Irish economy and highlights that no silver bullet exists. Energy efficiency is a resilient technology choice and is an enabler of low-carbon choices. Continued deployment of renewables in all modes of energy (electricity, heat and transport) is required, in particular the continued deployment of bioenergy in the heating and transport sectors.

Achieving the highest levels of decarbonisation will also require a focus on technologies that trap and remove emissions from the atmosphere. Carbon capture and storage may be required for industrial processes such as cement production and also in the power system when there are very high variable renewable electricity levels. The removal of carbon through direct air capture and the use of biomass with carbon capture and storage may also be required for net zero levels of ambition. The following were among the recommendations arising from this research:

- Further research is required on the implications of a net zero emissions economy for Ireland.
- The role and costs of hydrogen and new synthetic fuels in the future Irish economy require greater understanding.
- The role of (solid, liquid and gaseous) bioenergy, in particular for heating and transport, requires much greater policy consideration.
- The future role of CO_2 removal technologies in Ireland, including carbon capture and storage, requires further analysis.
- Significant increases in research on the societal dimensions of the transition towards a net zero GHG emissions future for Ireland are urgently required.

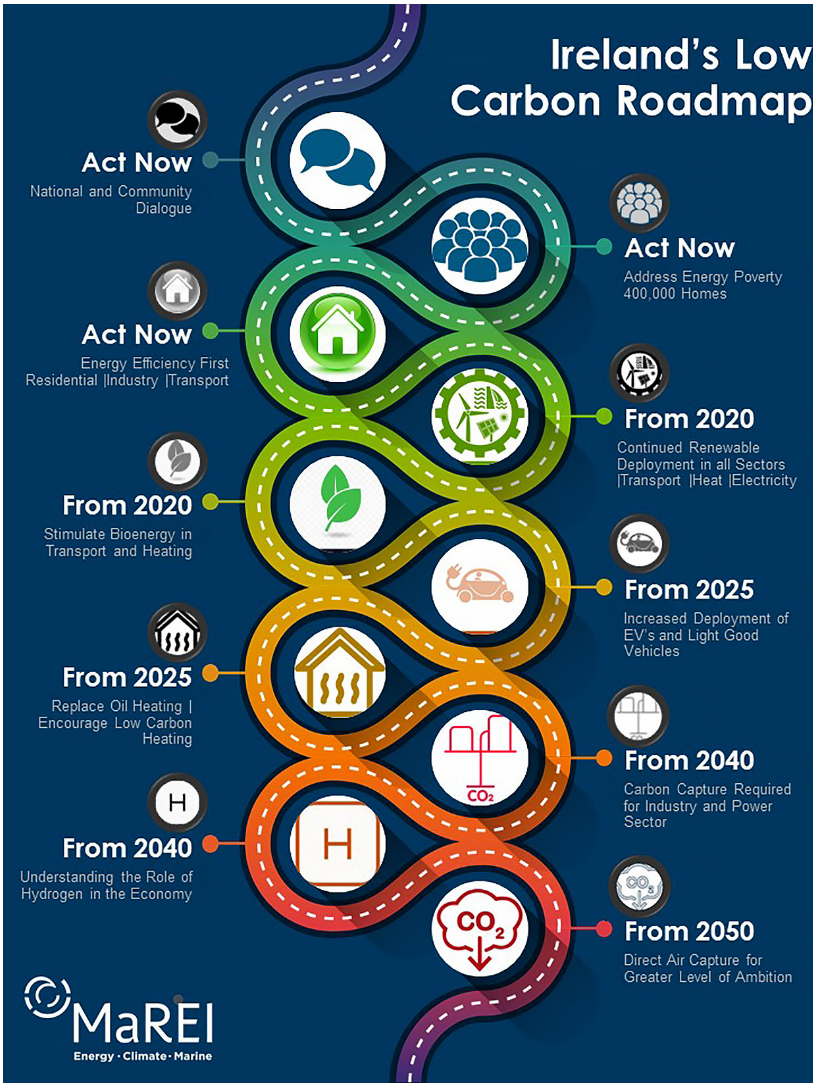


Figure ES.1. The MaREI Irish TIMES roadmap for Ireland's energy transition to a zero carbon future.

1 The Mitigation Challenge

1.1 From 2°C to 1.5°C: Outcomes of the Paris Agreement

The evidence is unequivocal: global anthropogenic emissions are leading to an average warming of the climate (IPCC, 2015). The global mean surface temperature is projected to increase by 3.7°C to 4.8°C during the 21st century without additional mitigation (Edenhofer *et al.*, 2014). Given the perilous balance between land level and rising sea level, small island states and low-lying countries require that temperature increases are limited to 1.5°C over the next century to avoid catastrophic impacts. The 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris marked a number of milestones in the course of international efforts on global climate action.

The Paris Agreement, reached in 2015, was very significant (UNFCCC, 2018). First, the global politically agreed ambition regarding climate action increased significantly, namely to hold "the increase in the global average temperature to *well below* 2°C above pre-industrial levels and *pursuing efforts* to limit the temperature increase to *1.5°C* above pre-industrial levels" while achieving "*a balance between* anthropogenic emissions by sources and removals by sinks of greenhouse gases (GHGs) in the second half of this century" (italics added for emphasis). Second, a record breaker in international law, the Paris Agreement was agreed in December 2015 and entered into force just 11 months later, in November 2016. This contrasts significantly with the Kyoto Protocol, which was agreed in 1997 but was not ratified until 2005.

A third key milestone arising from the Paris Agreement was the introduction of Nationally Determined Contributions (NDCs), representing what governments considered their countries could commit to, i.e. this was a "bottom-up" calculation and a presentation of emissions reduction potential. The NDC process formed a key input to the Paris Agreement, which, when signed in December 2015, included all 197 countries that had submitted NDCs. This also contrasted with the Kyoto Protocol, agreed in 1997, which set an overall target for 2010 of reducing GHG emissions in industrialised countries by 5% against 1990 levels over the period 2008–2012. The participating countries agreed to share and divide the target based on various formulae, hence the Kyoto Protocol was a "top-down" style of agreement (Leal-Arcas, 2011).

1.2 Implications of These Targets (Carbon Budgets)

The Paris Agreement enshrines restricting the global temperature increase to well below the 2°C limit, with the aim of limiting this increase to 1.5°C. This is significant for the remaining amount of GHG emissions that can be released into the atmosphere. The remaining global carbon budget for a 66% probability of limiting the temperature rise to 2°C has been estimated to be within the range 590–12,400 $GtCO_2$ (Friedlingstein *et al.*, 2014; Rogelj *et al.*, 2016). The recent Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR15) (IPCC, 2018) updated the remaining carbon budget range from 2018 onwards for a 66% probability, or for remaining below 2°C, to between 980 and 1320 $GtCO_2$ (–400 $GtCO_2$ to +250 $GtCO_2$ uncertainty range) (Rogelj *et al.*, 2019). Carbon budget uncertainty is largely driven by the dynamics of non-CO_2 GHGs, such as methane from agricultural emissions, and uncertainties in climate sensitivity (Rogelj *et al.*, 2018).

The remaining carbon budget to stay below 1.5°C by 2100 with a greater than 50% probability is estimated at 200–700 $GtCO_2$ (IPCC, 2015; Millar *et al.*, 2017; Rogelj *et al.*, 2019). The implications of this are highlighted in the IPCC SR15 report, with a key finding being that meeting a 1.5°C (2.7°F) target is possible but would require "deep emissions reductions" and "rapid, far-reaching and unprecedented changes in all aspects of society" (IPCC, 2018). The IPCC SR15 report concludes that, for ambitious emission reduction pathways with no or a limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions must decline by about 45% from 2010 levels by 2030 (40–60% interquartile range) and reach net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C, CO_2 emissions must decline by about 25% by 2030 (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Note that pathways that limit global warming to 1.5°C with no or a limited overshoot also involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010 emission levels).

2 The Irish TIMES Energy Systems Model

The MaREI Research Centre for Energy, Climate and Marine developed the Irish TIMES (The Integrated MARKAL-EFOM System) energy systems model in the period 2009–2017 [funded under the Environmental Protection Agency (EPA) Climate Change Research Programme] and used it to build a range of medium- (to 2020 and 2030) and long-term (to 2050) energy and emissions policy scenarios to inform policy decisions. Figure 2.1 provides a timeline for this research project and highlights a number of the key project milestones. Since 2018, the Irish TIMES model has been funded by the Department of Communications, Climate Action and Environment, to support the Technical Research and Modelling Group (TRAM) that reports to the Senior Officials' Group to the Cabinet Committee on Economic Infrastructure and Climate Change.

This report focuses on the Irish TIMES Phase 3 project, covering the period from November 2013 to October 2017. The project enabled MaREI, the Science Foundation Ireland (SFI) Research Centre for Energy, Climate and Marine, to further develop Irish TIMES, Ireland's only fully integrated, long-term energy systems optimisation model. It also built further research capacity in energy systems modelling within MaREI's Energy Policy and Modelling team at University College Cork's (UCC) Environmental Research Institute.

The Irish TIMES model is Ireland's only fully integrated long-term energy systems optimisation model. It is unique in its ability to provide least-cost cross-sectoral evidence-based analysis for climate and energy policy. The model represents the Irish energy system and its possible long-term evolution through a network of processes that transform, transport, distribute and convert energy from its supply sector (fuel mining, primary and secondary production, exogenous import and export) to its power generation sector (including also combined heat and power) and its demand sectors (residential, commercial and public services, agricultural, transport and industry).

2.1 How the Model Works (To Generate Least-cost Future Energy System Pathways)

Irish TIMES is an optimisation model. Its key role is to generate future energy system pathways for Ireland that meet our needs for energy at least cost. The objective function of the Irish TIMES model maximises total surplus. This is equivalent to minimising the total discounted energy system cost while respecting

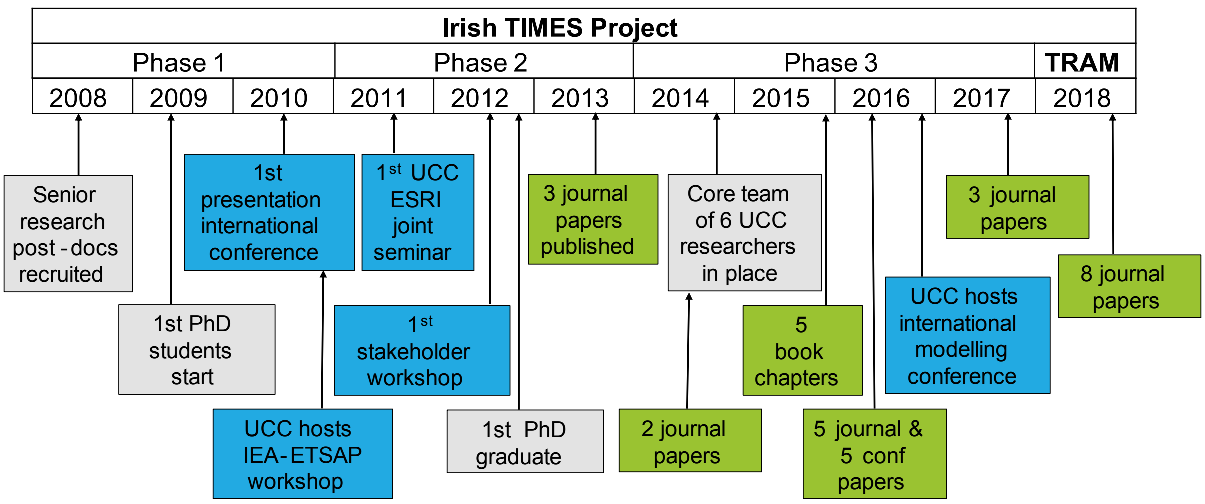


Figure 2.1. Timeline of the Irish TIMES energy systems modelling project. ESRI, Economic and Social Research Institute; IEA-ETSAP, International Energy Agency–Energy Technology Systems Analysis Program; UCC, University College Cork.

environmental and technical constraints, such as CO_2 emissions reductions targets for 1 year or over a period and renewable energy targets for specific time periods. The costs incorporated include investment costs and operation and maintenance costs plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon.

Valuable insights can be derived from comparing model scenario results that differ in terms of key input assumptions. We can explore different levels of climate mitigation ambition, for example. How can we meet a target of 80% reduction in CO_2 emissions by 2050 at least cost? How does this compare with a scenario in which we constrain the model to deliver a zero CO_2 emissions energy system by 2050? Outcomes from these analyses point to a number of overarching results (Deane *et al*., 2013), namely:

1. The Irish energy system can reduce emissions by 80% relative to 1990 but significant investment in energy efficiency and renewable energy technologies is required. Investment by 2050 may be 30% higher in a low-carbon energy system than in a business-as-usual scenario and this is offset by a 33% reduction in fuel costs.

2. Significant changes in infrastructure may be required. Electrification of heat and transport could increase the electricity share of energy use from 18% to between 25% and 40%. It is anticipated that networks will deliver more biogas than natural gas to final customers, in addition to the natural gas delivered to power plants with carbon capture and storage (CCS). Oil distribution could be replaced by liquid biofuel distribution, apart from kerosene use in aviation.

The scenarios can provide insights into the timing and scale of technology deployment required to meet constraints, as well as the potential costs, benefits and other implications (e.g. for energy efficiency, renewable energy and energy security) of different pathways. Technologies that emerge for meeting different constraints at least cost can provide a starting point for considering the policies and measures necessary to promote widespread adoption. For example, private car transport could be completely electrified by 2050 (Deane *et al*., 2013); residential heating may switch from oil and gas to air source heat pumps and biogas; natural gas may still be used in 2050 but at reduced levels and limited to electricity generation with CCS.

The model is built with the TIMES modelling framework. TIMES has been developed and made available through international collaborative research via the Energy Technology Systems Analysis Program (ETSAP),[1] a multilateral technology initiative that was initiated in 1976 under the aegis of the International Energy Agency (IEA), with the aim of carrying out a joint programme of energy technology systems analysis. TIMES is written in GAMS (General Algebraic Modelling Software) code and CPLEX and XPRESS are typically the solvers used. A key characteristic of this model generator is that the code is transparent and well documented, distributed free of charge, and maintained, improved and updated through a collaborative research initiative co-ordinated by ETSAP. The Irish TIMES team co-authored and edited a book published by Springer (Giannakidis *et al*., 2015) that provides a comprehensive introduction to TIMES and how it has been used to inform energy and climate policies around the world. Building on the success of this book, the team co-authored and edited a second book focusing on limiting global warming to well below 2°C, also published by Springer (Giannakidis *et al*., 2018).

2.2 Data Inputs (Economic Forecasts, Fuel Price Projections, Resource Projections, Technology Costs, Etc.)

The key inputs to a TIMES model are the demand component (energy service demands), the supply component (resource potential and costs), the policy component (e.g. maximum levels of CO_2 emissions or minimum levels of renewable energy) and the techno-economic component (technologies and associated costs to choose from). The model is driven by exogenous demand specified by the list of each energy service demand (disaggregation), actual values in the base year (calibration) and values for all milestone years until 2050 (projection).

TIMES models are not designed to reflect reality but it may be useful to consider how the results from these

1 See http://www.iea-etsap.org/ for more details (accessed 27 April 2020).

models compare with decisions taken in the real world. TIMES model results may, in a crude simplification, be essentially compared with those arising from the decisions of a benevolent system planner, making decisions on behalf of energy users in order to minimise energy systems costs. This assumes that the decisions that we take regarding energy use are driven by long-term internalised choices regarding technology in response to cost changes. These decisions are also taken with (the imperfect assumption of having) perfect prior information regarding future demands for energy services and with energy suppliers operating in perfect market conditions.

The model generator TIMES, and its predecessor MARKAL, are currently in use in nearly 200 institutions across 70 countries' regional energy systems, providing a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. They are usually applied to the analysis of the entire energy sector but may also be applied to study individual sectors in detail. They have been, and are being, used to generate energy systems models for local, national or multi-regional (including global) applications. They compute a dynamic intertemporal partial equilibrium on integrated energy markets with the objective (objective function) of producing least-cost energy systems while respecting environmental and many technical constraints.

The strong point of the TIMES modelling framework is that it combines a detailed, technology-rich database with an economically optimising solver. It can generate robust energy policy scenarios over medium to long time horizons and these can offer strategic insights into long-term policy formation. This is especially important for the energy sector, which has large capital investments with long project lifetimes. The Irish TIMES model does provide very useful guidance on how to achieve policy decisions (e.g. emissions targets) using a least-cost approach. The complex dynamics (incorporating technologies, fuel prices, infrastructures and capacity constraints) of the entire energy system can be analysed through this modelling approach to better inform policy choices.

Another key strength of integrated energy systems models is that they approach energy as a system rather than as a set of discrete non-interactive elements. This has the advantage of providing insights into the most important substitution options that are linked to the system as a whole, which cannot be understood when analysing a single technology, commodity or sector. A focus on the electricity sector, for example, risks excluding possible unforeseen step changes in electricity demand, because of, perhaps, the electrification of transport or of heating. Current energy systems are the result of complex country-dependent, multi-sector developments. By considering energy supply and demand across all sectors simultaneously, systems analysis applies systems principles to aid decision-makers in problems of identifying, quantifying and controlling a system.

As with all energy models, TIMES models also have a number of limitations that should be considered when interpreting the results and scenario analyses. In some instances, these are simply limitations associated with the structure of the model; they are inevitable, based on the way that the model is built. In other instances, they could be considered weaknesses and, in these cases, research should be carried out to generate improvements. The main limitations are as follows:

- Input assumption uncertainty: The results of the scenarios are linked to inherent uncertainties in the input assumptions, in particular fuel price forecasts, macroeconomic projections and technology cost projections. Although scenario analysis, by its nature, tries to counteract this uncertainty by producing a range of results, this uncertainty is nevertheless present. New uncertainty analysis techniques found that a number of technology choices, such as retrofitting, heat pumps and electric vehicles, are robust and resilient to varying input parameters.
- Limited macroeconomic feedback: TIMES models are generally not able to take into account feedbacks between the output of the energy system analysis and the macroeconomy. By incorporating macroeconomic feedback, it was found that, in the period to 2020, Ireland's annual gross domestic product (GDP) growth rates reduce from 4% to 2.2% in the most ambitious decarbonisation scenarios, in line with the Paris Agreement (Glynn *et al*., 2019).
- Citizens and society: TIMES models have limited capacity to simulate how individuals and communities will engage with the energy system, in terms of changing practice, decisions regarding technology purchase and infrastructure. This is a limitation of most energy (and indeed

macroeconomic) models, in that they are generally limited to individual consumer behaviour, which is in turn limited to simple price response behaviour, with non-price-related behaviour and citizen engagement with infrastructure generally very poorly treated.

- Power system operational characteristics: Technical characteristics, such as minimum stable generation, ramps rates, and minimum up and down times, play an important role in actual power system operation and planning, in particular in systems with high levels of variable renewables, and these are generally not adequately incorporated into energy system models such as TIMES. We have addressed this limitation by developing techniques to link energy system models such as TIMES to dedicated power system models. This technique has been used to demonstrate that greater levels of variable renewable integration are achievable in Europe. See section 3.6 for more details.

3 How Does Irish TIMES Support Policy?

The Irish TIMES model provides a range of energy system configurations for Ireland for the period to 2050 that deliver projected energy service demand requirements, optimised to least cost and subject to a range of policy constraints (Deane *et al*., 2013; DCENR, 2015; Glynn *et al*., 2015; Ó Gallachóir *et al*., 2016). It provides a means of testing energy policy choices and scenarios, of assessing the implications for the Irish economy and of assessing Ireland's energy mix and GHG emissions. It was previously used to inform Ireland's negotiations with the European Union (EU) regarding the 2030 emissions target for Ireland (Chiodi *et al*., 2015), the development of climate action legislation (Ó Gallachóir *et al*., 2016), the White Paper on Energy (Deane *et al*., 2013), Ireland's first National Mitigation Plan (NMP) (Curtin *et al*., 2017) and Ireland's National Energy and Climate Plan (Ó Gallachóir and Chiodi, 2018). Most recently, it has been used to inform Ireland's All of Government Plan on Climate Action (Ó Gallachóir *et al*., 2019). Figure 3.1 summarises the key contributions from the Irish TIMES project to national energy and climate policy over time.

3.1 Capacity Built: Modelling and Absorptive

This project has built significant capacity in Ireland in energy systems modelling. From a very low base, and by leveraging the initial financial support from the EPA and the Sustainable Energy Authority of Ireland (SEAI) through the Irish TIMES project, MaREI's Energy Policy and Modelling team at UCC grew to 30 researchers in 2017. The capacity that this team has developed has had a significant impact on increasing and improving the evidence underpinning energy and climate action policy decisions, in particular since 2013. A number of the researchers trained in energy systems modelling at MaREI throughout this period have brought this capacity to other organisations, including the SEAI, the International Renewable Energy Agency, the European Joint Research Centre and E4SMA (Energy Engineering Economic Environment Systems Modelling and Analysis).

This team has engaged strongly in international collaboration, in particular through the IEA Technology Collaboration Programme on energy systems modelling (IEA-ETSAP), with support from the SEAI. Initially, the direction of learning was one way, from the IEA-ETSAP community to MaREI. Over time, as MaREI's capacity has grown, this has transformed considerably and MaREI researchers are now contributing significantly to key modelling challenges facing IEA-ETSAP. This includes topics related to integrating energy systems models with power systems models (Deane *et al*., 2015), integrating energy systems models with macroeconomic models (Glynn *et al*., 2015a,b), improving the representation of transport modal shift in energy systems models (Daly *et al*., 2015) and improving how to generate

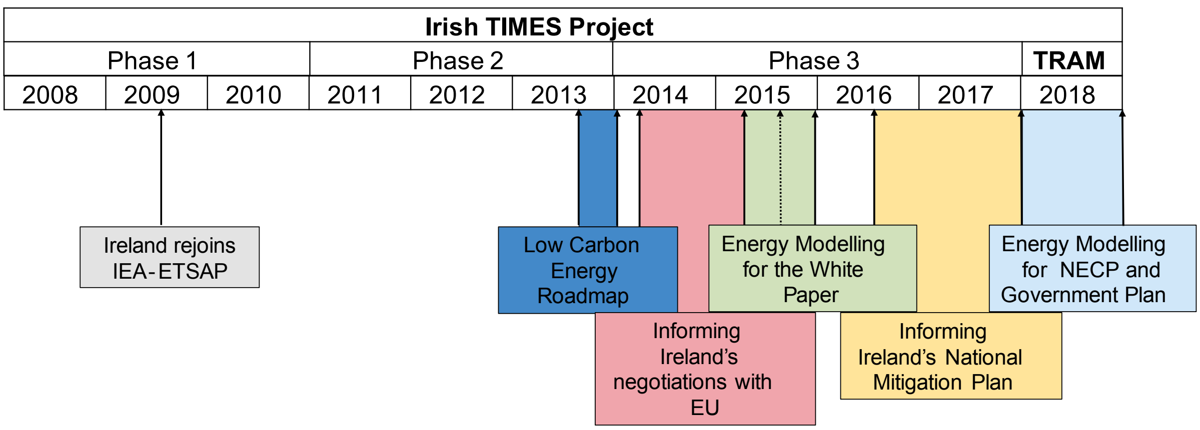


Figure 3.1. Key contributions to policies from Irish TIMES. NECP, National Energy and Climate Plan.

renewable energy marginal supply curves (Kempener *et al*., 2015). It also includes questions relating to the role of hydrogen (Hanley *et al*., 2018) and power-to-gas (McDonagh et *al*., 2018) in future energy system evolution.

In addition to building national capacity and contributing to international capacity building in the area of energy systems modelling, this project has also built absorptive capacity within the policy system in Ireland. The active engagement of the MaREI Energy Policy and Modelling research team with government departments, state agencies and other policy-informing research groups [in particular, the Economic and Social Research Institute (ESRI)] has increased the policy system's capacity to understand, absorb and utilise the Irish TIMES research findings. This has assisted Ireland in improving negotiations with the EU regarding energy and climate action targets and in improving national policy decisions (Chiodi *et al*., 2015).

3.2 Low Carbon Energy Roadmap (Climate Action Act)

The Irish government was planning to legislate for climate action and low carbon development and published a Heads of Bill (General Scheme of a Climate Action and Low Carbon Development Bill) in 2013 (DECLG, 2013). This raised key questions regarding the evolution of Ireland's future energy system to enable the transition to a low carbon future. The Irish TIMES model had the capacity to address these key questions.

In the period June–December 2013, the Department of the Environment, Community and Local Government commissioned UCC and the ESRI to produce a Low Carbon Energy Roadmap for Ireland to 2050 using the Irish TIMES model (Deane *et al*., 2013). The focus of this analysis was on technological changes in the energy system and the associated implications. A key policy question underpinning the analysis focused on the dynamics of the energy system moving towards a low carbon economy for two key time horizons, i.e. to 2050 and to 2030. The process involved modelling analysis and regular meetings and discussions with a number of government departments, providing technical advice and guidance on the development of a long-term strategy for Ireland. The purpose of the roadmap is to explore possible routes towards decarbonisation of the energy system, with a focus on achieving this at least cost to the economy and to society. The key issue is making well-informed policy choices. Hence, this roadmap does not stipulate which policies are necessary to achieve the transition; instead, it focuses on the key drivers and their implications for the energy system of moving to a low carbon economy.

The analysis focused on identifying ways of achieving 80% and 95% reductions in energy-related CO_2 emissions. The analysis also included the creation of a "business-as-usual" baseline (assuming no further policy actions), in order to enable comparisons between options and to help quantify the scale of the transition required. All scenarios focused on the period to 2050, building on the EPA's projections that cover the period to 2020. This analysis was also presented to the Oireachtas Committee considering the Bill (Ó Gallachóir, 2013), which was subsequently enacted in legislation in December 2013.

3.3 Negotiations with the European Commission Regarding 2030 Targets

In the period January–September 2014, the Irish TIMES model was used to inform Ireland's negotiating position with respect to the European Commission's proposal of a Climate and Energy Policy Framework for 2030 (EC, 2014a). Here, it was used to examine and provide answers to key questions arising from the proposed targets and, in particular, to scrutinise the findings of the modelling exercise (EC, 2014b) accompanying the proposal. The impact assessment accompanying the proposed climate and energy package is based on the modelling analysis developed mostly using the PRIMES (Price-Induced Market Equilibrium System) energy system model. It provides results for Ireland (and other Member States) arising from a scenario analysis of the EU achieving a 40% reduction in GHG emissions by 2030 relative to 1990.

The MaREI centre undertook analysis (Cahill *et al*., 2014) for the Irish government using the Irish TIMES energy system model to scrutinise the impact on the Irish energy system of the reduction in Irish GHG emissions indicated in the impact assessment. It addressed a series of key questions arising from the framework proposal:

- What level of GHG emissions reduction can be achieved in Ireland up to 2030, at a cost of €40/t?
- What are the marginal abatement costs in Ireland in 2030 associated with achieving the 33% emissions reduction relative to 2005 levels?
- What level of effort is required (measured as the increase in energy systems cost) to achieve a 33% GHG emissions reduction?
- What is the role of renewables in achieving the 33% emissions reduction?
- What is the cost-optimal effort distribution between Emissions Trading System (ETS) and non-ETS sectors of the economy?

Key outputs from the Irish TIMES model suggest that a 33% reduction in GHG emissions can be achieved at a marginal abatement cost of €151/t, significantly higher than the €40/t resulting from the PRIMES scenario analysis, whereas a reduction in GHG emissions of only 21% can be delivered at a marginal abatement cost of €40/t. Another key difference in the two models is also shown in the modal distribution of renewable energy. Although both analyses indicate renewable energy increases from 7% currently to 25% in 2030 as a share of gross final energy consumption, the PRIMES results point to a higher share of electricity from renewables [60% renewable energy sources for electricity (RES-E) compared with 51% RES-E from Irish TIMES]. In contrast, the Irish TIMES scenario analysis points to a higher share of thermal energy from renewables (38% compared with 17% in the PRIMES analysis).

This analysis was used by the government and strengthened Ireland's position during negotiations with the European Commission, with very positive feedback from the Irish delegation negotiating the Climate and Energy Policy Framework for 2030 in the weeks before the European Council meeting in October 2014.

3.4 Energy Modelling for the White Paper

The White Paper on Energy, *Ireland's Transition to a Low Carbon Energy Future 2015–2030* (DCENR, 2015), was launched in December 2015. It provided, at that time, a complete energy policy update of actions that the government intended to take in the energy sector, with a particular focus on the period up to 2030. The Irish TIMES model was used to provide technical assistance (Ó Gallachóir *et al.*, 2015) to inform the White Paper.

The process involved the researchers having many meetings with department officials, in particular over the period April–June 2015. The analysis undertaken not only focused on the energy transition to a low carbon future but also addressed a number of other key areas of policy, including the potential role of bioenergy in electricity generation, an assessment of the extent of energy poverty and how this might be addressed, and new approaches for quantifying energy security.

3.5 Energy Modelling for the National Mitigation Plan

The National Policy Position on Climate Action and Low Carbon Development (DCCAE, 2014) sets an ambition of achieving at least an 80% reduction in CO_2 emissions relative to 1990 levels. In addition, the EU has proposed a 2030 emissions reduction target for Ireland. The period to 2030 is critical on the journey to achieving this long-term objective; different levels of ambition in the medium term have implications for the long-term pathway and, conversely, the long-term ambition affects the choice between medium-term options. It is important to consider these interactions to develop a coherent decarbonisation strategy.

This analysis was undertaken in 2017 (Curtin *et al.*, 2017) to inform the development of Ireland's first NMP. We developed a NMP scenario (Figure 3.2) that brings together the medium-term mandatory obligations proposed by the EU and the longer-term national ambition. We compared this with a counterfactual business-as-usual case to explore the scale of the challenge.

The NMP scenario is therefore based on the following assumptions:

- overall CO_2 emissions are 80% below 1990 levels by 2050;
- for ETS emissions, a carbon price rises to €40/t by 2030 and emissions decline 2.2% per annum thereafter to 2050;
- Ireland meets its mandatory non-ETS target for 2030 agreed by the EU.

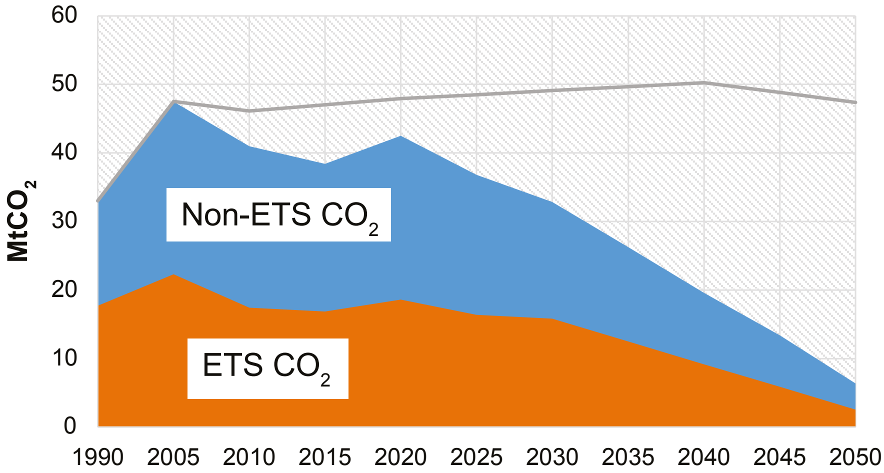


Figure 3.2. ETS and non-ETS energy emissions in the NMP scenario compared with business as usual (indicated by the grey line).

It should be noted that these assumptions reflect the difficulty of determining how a national target can be achieved within the context of an EU-wide ETS. National governments have little final influence on whether ETS emissions reductions occur on their territory unless a carbon price floor (such as that in the UK) is considered; ultimately, this depends on decisions taken by the installations covered and the ETS carbon price. EU Member States have taken different approaches to calculating compliance with national targets within this context. Recently, MaREI, in co-operation with Ireland's Climate Change Advisory Council, has investigated the impact of a carbon price floor in north-west Europe (Deane *et al.*, 2018).

In the NMP scenario, overall emissions fall to 6.3 $MtCO_2$ by 2050. There is an overall reduction of 76% (to 3.8 $MtCO_2$) in non-ETS emissions by 2050 relative to 1990 levels, whereas ETS emissions fall by 85% (to 2.6 $MtCO_2$) relative to 1990 levels. By comparison, in the business-as-usual scenario, CO_2 emissions increase from 33 $MtCO_2$ in 1990 to over 49 $MtCO_2$ in 2030, before falling to 47.3 $MtCO_2$ by 2050. CO_2 emissions in the business-as-usual scenario are therefore 43% higher by 2050 than in 1990 (see Figure 3.2).

It is notable that achieving further emissions reductions before 2020 would ease the challenge post 2020, to avoid the sudden switch from increasing to decreasing emissions. Also notable is the slope of the decarbonisation trend between 2020 and 2030 in the NMP scenario, which appears coherent with meeting the 80% reduction required by the National Policy Position. However, this depends on ETS emissions reductions, which Ireland has less control over. Although supports for renewable electricity would increase ETS decarbonisation, if implemented in many Member States these will further dampen the ETS price.

3.6 Engagement with International Bodies, EU PLEXOS and Global TIAM Models

A recognised limitation of the TIMES model is its poor technical portrayal of detailed electricity sector elements that are important for a complete understanding of variable renewable electricity generation, such as solar, wind and tidal, and the greater interconnection with neighbouring countries. Techniques have been developed in UCC to overcome these limitations (Deane *et al.*, 2012, 2014, 2017) and enhance policy decisions, not only at national level but also at EU level (Collins *et al.*, 2017, 2018a; Gaffney *et al.*, 2018).

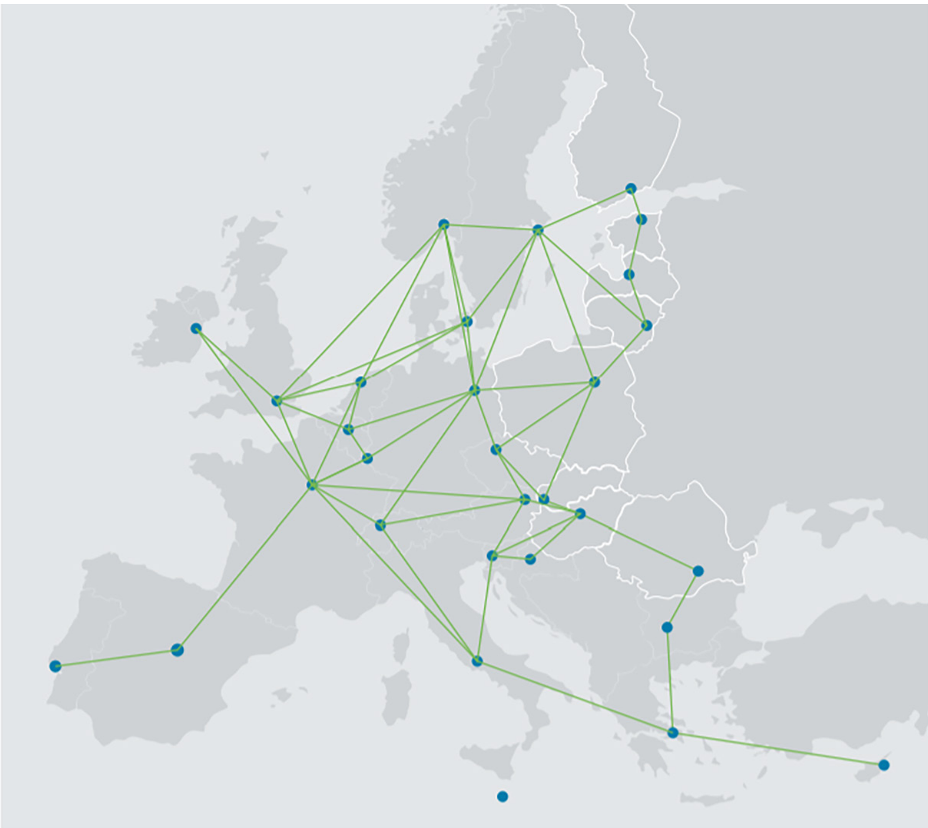
An example of this research has been the collaboration between UCC and the International Renewable Energy Agency (IRENA), to examine the greater ambition of the EU 2030 targets in light of decreasing renewable energy costs. The study (IRENA/EC, 2018), prepared in co-operation with the European Commission, identified cost-effective renewable energy options for all EU Member States, spanning a wide range of sectors and technologies, with UCC contributing to the technical modelling of the electricity sector (Collins *et al*., 2018b), by building and using an EU PLEXOS electricity dispatch model (Figure 3.3).

A key finding of the report was that the EU could double the renewable share in its energy mix, cost-effectively, from 17% in 2015 to 34% in 2030. In June 2018, the EU Parliament and Council agreed to increase the EU 2030 ambition for renewable energy from a 27% share of energy from renewables (agreed previously in 2014) to at least 32% of the Union's gross final consumption in 2030, with an upwards revision clause by 2023.

A key focus of UCC's research in this area has been transparency, access and openness. All of UCC's EU PLEXOS electricity models are publicly available. Recent research in collaboration with Imperial College London and ETH Zurich was highlighted in *Nature*[2] and published in *Joule* under an open access agreement (Collins *et al*., 2018a).

Recent international engagement with the Deep Decarbonization Pathways Project[3] has also commenced, with UCC providing input on potential pathways to decarbonisation for Ireland.

Modelling capacity learned during the development of the Irish TIMES model has enabled UCC researchers to take a leading role in the ETSAP-TIMES Integrated Assessment Model (TIAM) developers group, the global TIMES model developed within the IEA-ETSAP Technology Collaboration Programme. Collaboration at the global level has led to a paper on understanding the role of local air pollution in equitable decarbonisation scenarios (Kypreos *et al*., 2013) and multi-author book chapters on energy systems consistent with the Paris Agreement (Karlsson *et al*., 2018; Winning *et al*., 2018) and methods of linking to macroeconomic models (Glynn *et al*., 2015a,b), as well as multiple ongoing projects. This expertise has also led to MaREI researchers being invited to knowledge transfer workshops, the



Source: IRENA and University College Cork based on ENTSO-E (2016). Background map: OpenStreetMap®

Figure 3.3. Schematic presentation of geographical coverage of MaREI's EU PLEXOS model.

2 See https://www.nature.com/articles/d41586-018-05820-8 (accessed 9 December 2019).

3 See http://deepdecarbonization.org/ (accessed 6 March 2020).

European Commission, the US Department of Energy and expert review and advisory panels, as well as being invited by the South Korean government to lead workshops. This expertise and collaboration provides insights into and advanced understanding of the state-of-the-art of climate science and energy systems modelling to provide impact and insights in Ireland before government policy prescription (Glynn *et al*., 2019), which was not the case prior to the Irish TIMES project. Ongoing TIAM collaboration with Imperial College London, Oxford University, Danish Technical University, Politecnico di Milano, Utrecht University and Tsinghua University have placed Irish TIMES alumni researchers at the forefront of energy systems modelling innovation and zero carbon technology understanding (Glynn *et al*., 2017a,b, 2018a,b,c; Panose *et al*., 2017; Lehtilla *et al*., 2018; Realmonte *et al*., 2019; Sharma *et al*., 2019).

4 State of Knowledge on the Role of Technology in Mitigation

Recent innovative methodological developments at MaREI with the Irish TIMES model enable us to efficiently generate multiple scenarios with varying levels of mitigation ambition (Yue, 2019). This enables MaREI to produce innovative marginal abatement cost curves (MACCs) with a focus on policy insights for maximising technology opportunities. Figure 4.1 presents one of the outputs of this analysis. Here, the *x*-axis represents percentage emissions reductions in 2050 relative to the reference scenario, varying from 0% to 95%. It is worth noting that, in the reference scenario, CO_2 emissions are 4% above 1990 levels. The red line in Figure 4.1 tracks the marginal abatement cost, which increases with increasing mitigation ambition and mostly remains under €500/t CO_2 until the mitigation ambition exceeds 87%.

Figure 4.1 also shows which technologies contribute to the mitigation as the ambition increases. This information is also presented in Table 4.1. It clarifies why, for example, biomass boilers appear close to the *y*-axis in Figure 4.1; they are cheap relative to other mitigation options. It also identifies the extent of mitigation potential associated with different mitigation measures.

The Irish TIMES model is a least-cost optimisation model. The reference scenario is typically set up to explore how a future energy system will meet our energy service demand requirements at least cost. Many energy efficiency measures appear in MACCs below the line, indicating that the cost savings achieved over time exceed the initial investment and therefore represent a negative cost measure. In an optimisation model, these measures are selected in the reference scenario because they represent part of the least-cost solution. Hence, the starting point in energy systems optimisation scenario analysis tends to already include many energy efficiency measures.

4.1 Key Role of Energy Efficiency

To reveal the significant role played by energy efficiency in energy transition, we impose some restrictions on the technology choices that can be made in the reference scenario, in order to reflect the business-as-usual world, where many market, information and other barriers mitigate the take up of energy efficiency measures.

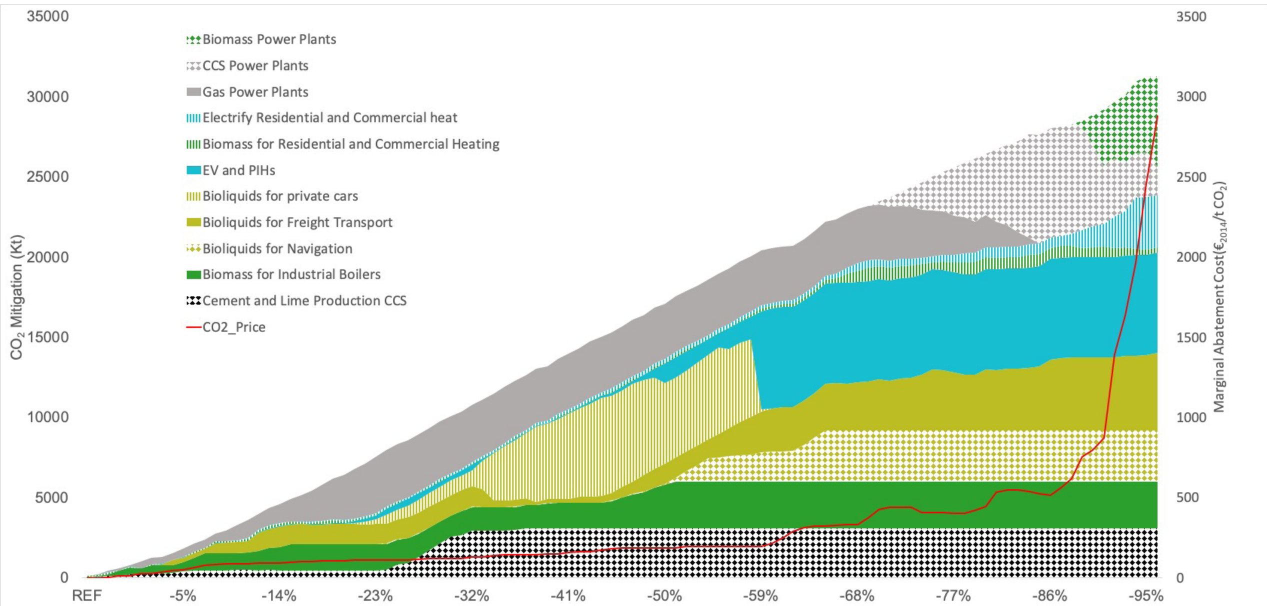


Figure 4.1. MACC for Ireland in 2050 for different levels of mitigation ambition. REF, reference scenario.

Table 4.1. Relative costs of key mitigation options for the reference scenario MACC

Mitigation measure	Technology group	MAC range (€/tCO_2, 2014)	Mitigation potential relative to the reference scenario (kt)
Biomass boilers	Industrial heating	15–189	2900
Gas power plants	Power generation	35–107	3600
Industrial CCS	Cement production	107–141	3700
PIHs and EVs	Private cars	180–240	6250
Navigation biofuel	Navigation	188–316	3200
Freight biofuel	Freight transport	159–541	4800
Biomass	Building heating	279–425	800
Gas CCS plants	Power generation	425–495	6800
Electrification	Building heating	528–3964	3300
Biomass plants	Power generation	769–3964	5600

EV, electric vehicle; PIH, plug-in hybrid.

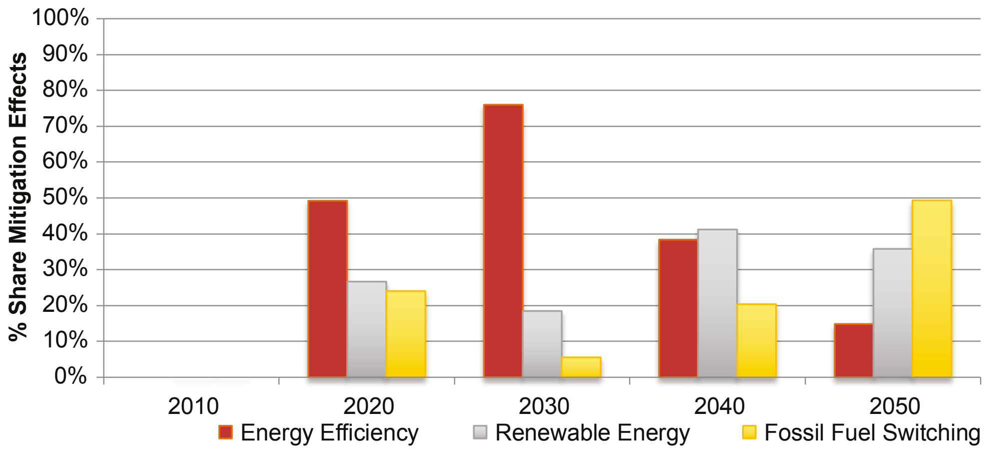


Figure 4.2. Comparing business as usual with the NMP to show the key role of energy efficiency.

Figure 4.2 compares a business-as-usual scenario with a NMP scenario, drawn from analysis (Ó Gallachóir and Chiodi, 2018) used to inform the government's NMP. Figure 4.2 clearly demonstrates not only the significance of early action on energy efficiency but also the extent of mitigation potential and the key role that energy efficiency can play in the energy transition. It is worth pointing out, however, that there are significant challenges in delivering on this potential because it tends to require many individual decision-makers (e.g. building owners) to make active decisions to undertake energy efficiency actions.

4.2 Strengthened Importance of Renewable Energy

Renewable energy made up 11% of the gross final energy consumption in Ireland in 2018. Although strong advances have been made in renewable electricity, electricity constitutes approximately 20% of final energy consumption in Ireland today, with the remainder being heat and transport. Technology mitigation options for heat and transport are generally understood to be more expensive and challenging to implement. As well as higher upfront initial costs (from 60% extra for electric vehicles to over 300% extra for heat pumps), research from SEAI (2018) demonstrates a low ratio of consumer engagement to final technology uptake because consumers have to make active decisions. Active decisions take time and effort as people have to learn about new technologies and then make a financial decision to buy.

Recent research by MaREI with the TIMES model has focused on the future role of hydrogen in transport (McDonagh *et al.*, 2018), finding that hydrogen's use in energy systems is complex because of its relationship with other energy sources. It was shown that bioenergy can act as both a competitor and a driver for hydrogen energy, along with increased electrification and high renewable electricity scenarios. Hydrogen mainly emerges as a technology mitigation option post 2030. The uncertainty and complexity surrounding hydrogen is often a result of the difficulty of representing hydrogen technologies and systems in energy system models (Hanley *et al.,* 2018).

Natural gas and synthetic gas have also been explored as technology options using the Irish TIMES model (Chiodi *et al*., 2015). Power-to-gas has been proposed as a means of producing advanced renewable gaseous transport fuel while providing ancillary services to the electricity grid through decentralised small-scale installations. Our research found that electricity costs and the capacity factor were the most sensitive parameters for understanding the future role of power-to-gas and that valorisation of the produced oxygen and payments for ancillary services would lower the investment barrier.

4.3 Trade-offs between Electricity, Heat and Transport

Electricity is emissions free at its point of use and the decarbonisation of the power sector can enable decarbonisation elsewhere in the economy, such as in the area of heat and transport. MaREI's research on low carbon pathways for Ireland indicate a significant increase in electrification. The share of low carbon electricity supply will increase from the current level of approximately 20% to almost 50% by 2050, and fossil fuel power generation without carbon capture is expected to be almost entirely phased out. It is not known whether this increase in electrification can be managed with current infrastructure and how the sectors of heat and transport will impact the overall reliability and stability of the power system. Current enabling and mitigation technologies such as smart meters, battery storage, heat storage and widespread deployment of variable renewables, coupled with increased interconnection across Europe, are currently being investigated at MaREI (Gaffney *et al.*, 2018); however, it remains to be seen if the optimal mix of these technologies will deliver an energy system that is aligned with the goals of the Paris Agreement.

4.4 Carbon Capture and Storage

The IPCC Special Report on Global Warming of 1.5°C highlighted the need for greater research and development into understanding of the impact of CCS on climate stabilisation scenarios. MaREI has recently completed a state-of-the-art review of CCS in climate stabilisation scenarios of global integrated assessment models (IAMs) (IEAGHG, 2019), highlighting some of the methodological weaknesses and uncertainties in CCS and direct air CCS modelling in IAMs, in contrast to better potential representation in energy systems models. Without CCS, along with other urgent forms of CO_2 removal, the costs of temperature stabilisation rapidly increase (median ~138%,16th to 84th percentile 29% to 297%). Analysis at MaREI examined the impacts of high levels of renewable energy and negative emissions technologies on exploratory visions of the future EU power system in 2050 (Gaffney *et al.*, 2018). The research highlighted the importance of negative emissions technologies, such as CCS and direct air capture of CO_2, in future EU systems and demonstrated that net negative emissions technology can contribute to power system operations without breaching regional sustainable biomass potentials and national CO_2 geological storage limits. This technology becomes increasingly important for higher levels of ambition post 2040.

5 Increasing Ireland's Ambition in Line with the Paris Agreement

Parts of this chapter, including Figures 5.1 and 5.2, have been reproduced from Glynn *et al.* (2019).

A further key methodological innovation undertaken in this project is the introduction of a hybrid general equilibrium model, with feedback between the energy system and the macroeconomy. This outlines how the overall economy may react to a decarbonising energy system. The induced changes in economic growth, sectoral energy service demands, consumption and investments are brought about by the substitution of investment capital and human capital with productive energy services. The method applied here is the first published national application of this decomposition general equilibrium method (MSA – Macro Stand Alone) to calculate first-order macroeconomic impacts of decarbonising the energy system on the Irish economy (Glynn *et al.*, 2019).

The cumulative carbon budgets for Ireland utilised in this analysis range from 766 $MtCO_2$ to 128 $MtCO_2$ from 2015 to the end of the time horizon (2070). They are derived from the Irish population share of 0.064% of the global population and the same 0.064% share of the remaining global carbon budgets. These carbon budgets relate to a 66% probability of achieving a 2°C limit, to a 50% probability of reaching a 1.5°C limit, and are chosen to span the technically feasible range of territorial mitigation. This approach can be justified by the fact that the Irish population as a percentage of the global population has been remarkably stable over the last 50 years and is projected to remain so. In addition, Ireland is not in significant carbon debt; Irish historical CO_2 emissions from fossil fuel combustion and cement production from 1751 to 2015 are estimated at approximately 2.04 $GtCO_2$, which is less than 0.064% of 3200 $GtCO_2$, i.e. the Irish per-capita share of the all-time 2°C global carbon budget. However, Ireland has consumed more than its per-capita share of a global 1.5°C carbon budget. Irish per-capita territorial CO_2 emissions are now at 8.4 tCO_2 per person – nearly twice the global average – and are growing.

This analysis estimates GDP losses, changes in consumption and changes in investment for a range of deep decarbonisation scenarios. We start with the national target of an 80% reduction in energy system CO_2 emissions by 2050, and then increase ambition with equitable per-capita shares of the remaining global carbon budgets with sensitivity to grid inertial limits, energy service demand reduction, bioenergy carbon capture and storage (BECCS), CCS and bioenergy imports in the Irish context.

5.1 Scenario Definitions and Variants

The 38 scenarios considered in this analysis are illustrated in Figure 5.1. These scenarios are chosen to outline the range of potential energy system changes under differing effort-sharing carbon budgets, based on equitable per-capita shares of the remaining global carbon budgets. We do not explore emissions inertia grandfathering type constraints where current national per-capita emissions converge to a global average at a point in the future, increasing what could be perceived as an equitable carbon budget. Scenario variants are used to account for uncertainty in climate mitigation policy choices, their implied constraints, immediate action versus delayed action, technology availability and energy service demand responses to macroeconomic feedback. The main scenario variants are as follows:

- REF – reference scenario. This scenario shows the least-cost optimal energy system evolution to 2070 in the absence of emissions constraints.
- CO2-80. This scenario achieves at least an 80% reduction in CO_2 emissions relative to 1990 by 2050, in line with Ireland's national policy position on climate action.

- 766 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 766 $MtCO_2$ between 2015 and 2070, without interim CO_2-80 annual emissions pathway targets. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 1200 $GtCO_2$ consistent with a 66% probability of meeting a 2°C target with immediate action. This scenario has its solution fixed to the reference solution to 2015 and evolves thereafter, showing what a post Paris Agreement mitigation pathway with immediate action from 2015 might have looked like.
- 638 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 638 $MtCO_2$ between 2020 and 2070 without interim emissions pathway targets, with the results fixed to the reference case before 2020. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 1000 $GtCO_2$ consistent with a 66% probability of meeting a 2°C target with mitigation action commencing in 2020, and where exogenous non-CO_2 emissions are at the low end of the feasible global range.
- 376 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 376 $MtCO_2$ between 2020 and 2070, without interim emissions pathway targets, with the results fixed to the reference case before 2020. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 590 $GtCO_2$ consistent with a 66% probability of meeting a 2°C target with mitigation action commencing in 2020, and where exogenous non-CO_2 emissions are at the high end of the feasible global range. Note that Ireland has high non-CO_2 agricultural emissions.
- 223 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 223 $MtCO_2$ between 2015 and 2070 without interim emissions pathway targets. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 350 $GtCO_2$ consistent with a 50% probability of meeting a 1.5°C target in 2100 with immediate action in 2015.
- 128 $MtCO_2$. This scenario applies a cumulative CO_2 budget of 128 $MtCO_2$ between 2015 and 2070 without interim emissions pathway targets. This constraint is based on an equitable population weighted (0.064%) carbon budget of future emissions of 200 $GtCO_2$ consistent with a 66% probability of meeting a 1.5°C target in 2100 with immediate action in 2015. (Note that none of the 128-$MtCO_2$ scenarios proved technically feasible.)

The scenario variants below can be run together in combination and most scenarios combine the MSA scenario variant to estimate price response and demand feedback with other constraints imposed by another scenario variant. Each carbon budget scenario

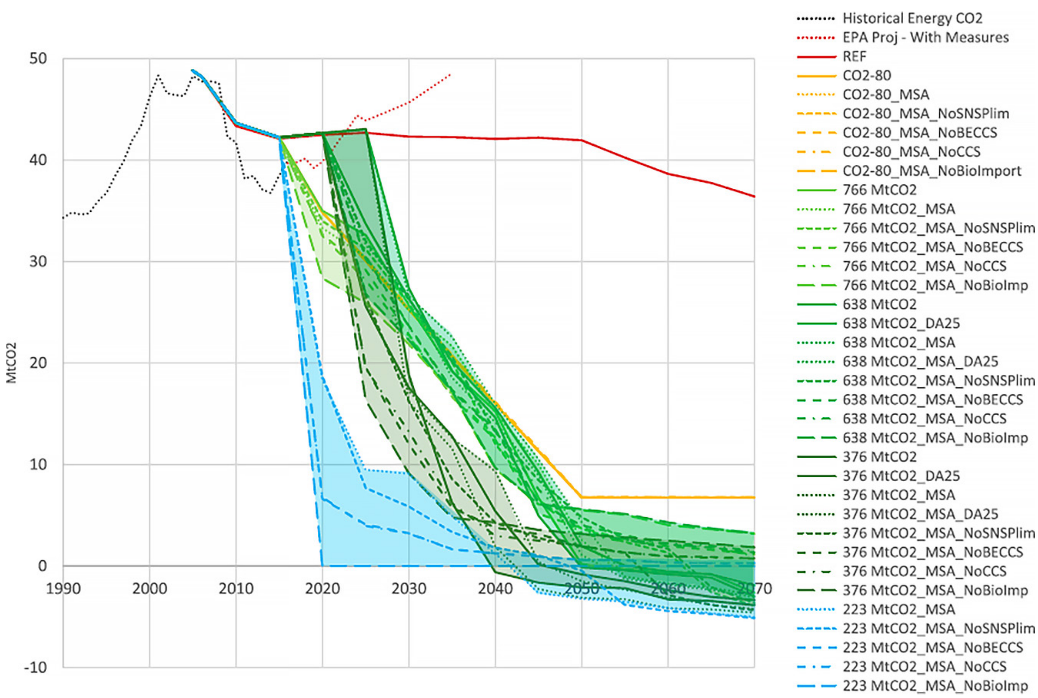


Figure 5.1. Scenario pathways and variants. REF, reference scenario.

is also run without MSA (macroeconomic feedback) to show the effect of an inelastic demand response.

- MSA. This scenario variant incorporates the MSA algorithm to calculate demand responses and macroeconomic feedback in a general equilibrium.
- DA25. This scenario variant delays mitigation action further to 2025 by fixing the scenario to continue along the reference path to 2025.
- NoSNSPLim. This scenario variant removes the default limit on system non-synchronous penetration of variable renewable generation, which represents the inertial limits of the Irish electricity grid. This constraint controls for the non-synchronous nature of generators with low inertial mass such as wind turbines and the potential frequency fluctuations these generators can induce upon an island grid.
- NoBECCS. This scenario variant does not allow BECCS in the power generation sector of the energy system model.
- NoCCS. This scenario variant does not allow CCS in the power generation sector of the energy system model. Note that CCS is still allowed in industry for cement production in this scenario variant.
- NoBioImp. This scenario variant only allows domestic bioenergy to be utilised within the energy system and does not allow bioenergy imports.

5.2 Results

Irish CO_2 emissions in the energy system are estimated in the official national GHG projections to rise from 38.5 $MtCO_2e$ in 2015 to 48.5 $MtCO_2e$ in 2035 as Irish economic activity continues to grow (EPA, 2017).

Under the reference case scenario in this analysis, CO_2 emissions do not follow a recovery path as with economic recovery per se, but find an optimally efficient energy system under reference macroeconomic conditions and show a flat projection to 42.2 $MtCO_2e$ in 2050. The three largest CO_2-emitting sectors in the reference scenario in 2050 are transport at 14.8 $MtCO_2$, electricity generation at 9.4 $MtCO_2$ and industry at 6.6 $MtCO_2$.

The CO_2-80 scenarios follow EU decline rates of 2.2%/year to final emissions of 6.8 $MtCO_2$ in 2050. The cumulative carbon budget constraint scenario of 766 $MtCO_2$, consistent with the 2°C target with 66% probability with immediate action, results in an 81–99% emissions reduction by 2050 from 1990 levels depending on available technology options and demand reduction options within the economy.

The cumulative carbon budget constraint scenarios of 638 $MtCO_2$–376 $MtCO_2$, consistent with the 2°C target with > 66% probability with delayed action until 2020 result in an 81–105% emissions reduction by 2050, again on 1990 levels. Faster emissions reduction rates are required in the medium term as a result of delayed action, with economic feedback enabling some optimisation of discounted welfare and GDP losses while balancing medium-term emissions reductions and long-term abatement costs. Delayed action between 2015 and 2020 has considerable impacts on the rates of decarbonisation required for a 2°C consistent mitigation pathway. Immediate decarbonisation allows slower emissions reductions of 1.6–2 $MtCO_2$/year for a 2°C target, as opposed to the delayed action case whereby CO_2 emissions need to be reduced by 1.6–3 $MtCO_2$/year by 2030 if energy system emissions do not peak until 2020. For a 1.5°C target, emissions reductions need to be immediate and in the range of 3.5–3.9 $MtCO_2$/year. Annual emissions are reduced by at least half, to 18.3 $MtCO_2$, in 2020 for a 1.5°C consistent scenario using the 223 $MtCO_2$ budget scenario, slowing to near net zero by 2050. Further details are in Figure 5.1.

The electricity generation sector covered by the EU ETS and the transport sector are the energy system sectors that most require aggressive decarbonising. Deep decarbonisation using a cumulative carbon budget of 128 $MtCO_2$ without macroeconomic demand reductions or bioenergy imports are infeasible in this model version.

The range of marginal abatement costs of CO_2 are logarithmic in scale across the 2°C set of scenarios. CO_2 abatement costs begin in 2020 at €75/tCO_2 and by 2025 range from €96/tCO_2 to €640/tCO_2, with a median value of €132/tCO_2, rising to €362–3308/tCO_2 in 2050 in real terms. For the 1.5°C consistent carbon budgets, the technically feasible scenarios' abatement costs range from €965/tCO_2 to €3080/tCO_2 in 2020 and rise to greater than €8100/tCO_2 by 2050.

Figure 5.2 summarises the scenario results for 2030 and 2050, focusing on the overall energy use fuel mix and also the electricity generation fuel mix.

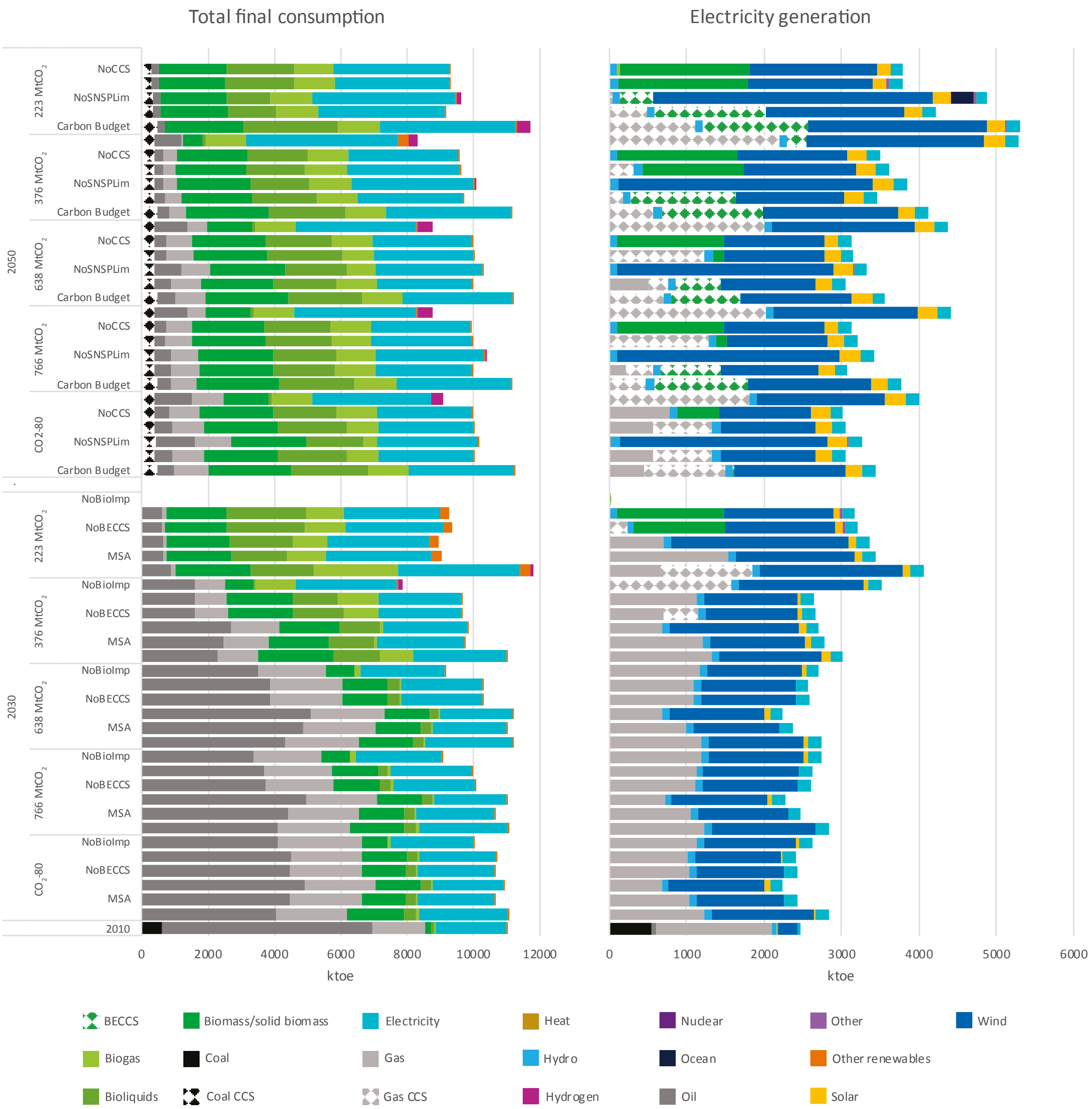


Figure 5.2. Deep decarbonisation scenario results for overall energy use and electricity generation fuel mix in Ireland.

Focusing on the overall energy use results for 2030, it is clear that, as the mitigation ambition increases, there is a significant decrease in the share of oil and a parallel increase in the share of bioenergy. Here, bioenergy comprises solid biomass, liquid biofuels and biogas. In the 1.5°C consistent 223-MtCO_2 scenario, bioenergy accounts for at least 50% of energy use by 2030, effectively displacing oil's current dominance in Ireland's energy use. There is also a significant increase in the role of electricity in Ireland's energy mix, arising from the electrification of the subsectors of transport and heat. The electricity fuel mix also varies significantly across scenarios, with increasing levels of wind energy as the mitigation target increases.

Although the role of energy efficiency, the growth of electrification and the increase in renewable electricity are reflected in the political and media discourse on climate action in Ireland, the potential contribution from bioenergy reflected in this analysis is largely ignored.

Moving to the 2050 scenario results, there is less variation in the overall energy use fuel mix, with bioenergy dominating, followed by electricity. Future electricity generation in Ireland is provided through a combination of increased wind power and thermal power plants with CCS technology. The thermal power plants are fuelled by either gas or bioenergy, depending on the decarbonisation ambition.

6 Conclusions and Recommendations

The MaREI Centre's Energy Policy and Modelling team at UCC's Environmental Research Institute developed the Irish TIMES energy systems model in the period 2009–2017 (funded under the EPA Climate Change Research Programme) and used it to build a range of medium-term (to 2020 and 2030) and long-term (to 2050) energy and emissions policy scenarios to inform policy decisions.

This report focuses on the Irish TIMES Phase 3 project, covering the period November 2013–October 2017. The project enabled MaREI, the SFI Research Centre for Energy, Climate and Marine, to further develop the Irish TIMES model. It also built further research capacity in energy systems modelling within MaREI's Energy Policy and Modelling team at UCC.

The Irish TIMES model is Ireland's only fully integrated long-term energy systems optimisation model. It is unique in its ability to provide least-cost, cross-sectoral evidenced-based analysis for climate and energy policy. The Irish TIMES model represents the Irish energy system and its possible long-term evolution through a network of processes that transform, transport, distribute and convert energy from its supply sector (fuel mining, primary and secondary production, exogenous import and export) to its power generation sector (including also combined heat and power) and its demand sectors (residential, commercial and public services, agricultural, transport and industry).

The key methodological developments achieved in this project were as follows:

- *Development 1*. The Irish TIMES model was improved to include negative emissions technologies. This allowed MaREI to build net zero emissions scenarios for Ireland that are consistent with the Paris Agreement.
- *Development 2*. This project enabled Irish energy modelling researchers to take a leadership role in developing the EU PLEXOS electricity and gas energy systems model and the global TIAM model.

This project contributed directly to improving energy and climate action policy development in Ireland.

The research capacity in MaREI's Energy Policy and Modelling team at UCC that this project funded was effectively utilised to inform (1) Ireland's negotiations with the EU in 2014 regarding the 2030 emissions target for Ireland, (2) the White Paper on Energy in 2015, (3) Ireland's first NMP in 2017 and (4) the government's Climate Action Plan 2019.

- *Policy outcome 1*. MaREI used the models developed in this project to support the Irish government in negotiating with the European Commission in 2014. The outcome was agreement on Ireland's target of a 30% reduction in non-ETS GHG emissions by 2030 relative to 2005 levels.
- *Policy outcome 2*. MaREI carried out scenario analysis using the models developed in this project on topics relating to decarbonising energy, energy security and addressing energy poverty to support the Department of Communications, Energy and Natural Resources during the summer of 2015. The outcome was the White Paper on Energy, *Ireland's Transition to a Low Carbon Energy Future 2015–2030*, published in December 2015.
- *Policy outcome 3*. MaREI used the models developed in this project to inform the government's first NMP in 2017. This analysis focused on how to meet Ireland's mandatory target under EU legislation for GHG emissions reduction by 2030.
- *Policy outcome 4*. MaREI used the models developed in this project to inform the government's Climate Action Plan in 2019. This analysis focused on increasing Ireland's long-term ambition to 2050 beyond the 80% target and on how this aligns with Ireland's mandatory target under EU legislation for GHG emissions reduction by 2030.

6.1 Recommendations

This report focuses on the role of clean technologies in all sectors of the Irish economy and highlights that no silver bullets exist. Many technologies are required across all sectors. Energy efficiency is a resilient technology choice and is an enabler of low carbon choices. Continued deployment of renewables in all modes of energy (electricity, heat and transport) is required, in particular the continued deployment of bioenergy in the heating and transport sectors.

Achieving the highest levels of decarbonisation will, however, require a focus on technologies that not only reduce carbon emissions but also trap and remove emissions from the atmosphere. CCS may be required for industrial processes such as cement production, and also in the power system when there are very high variable renewable electricity levels. The removal of carbon through direct air capture and the use of biomass with CCS may also be required for net zero levels of ambition.

The recommendations arising from this research are outlined in Figure 6.1 as an infographic roadmap for Ireland's energy transition to a zero carbon future. In addition, five key recommendations are as follows:

1. *Recommendation 1*. The implications of a net zero emissions economy are yet to be fully explored and understood for Ireland. Further research is required in this area.

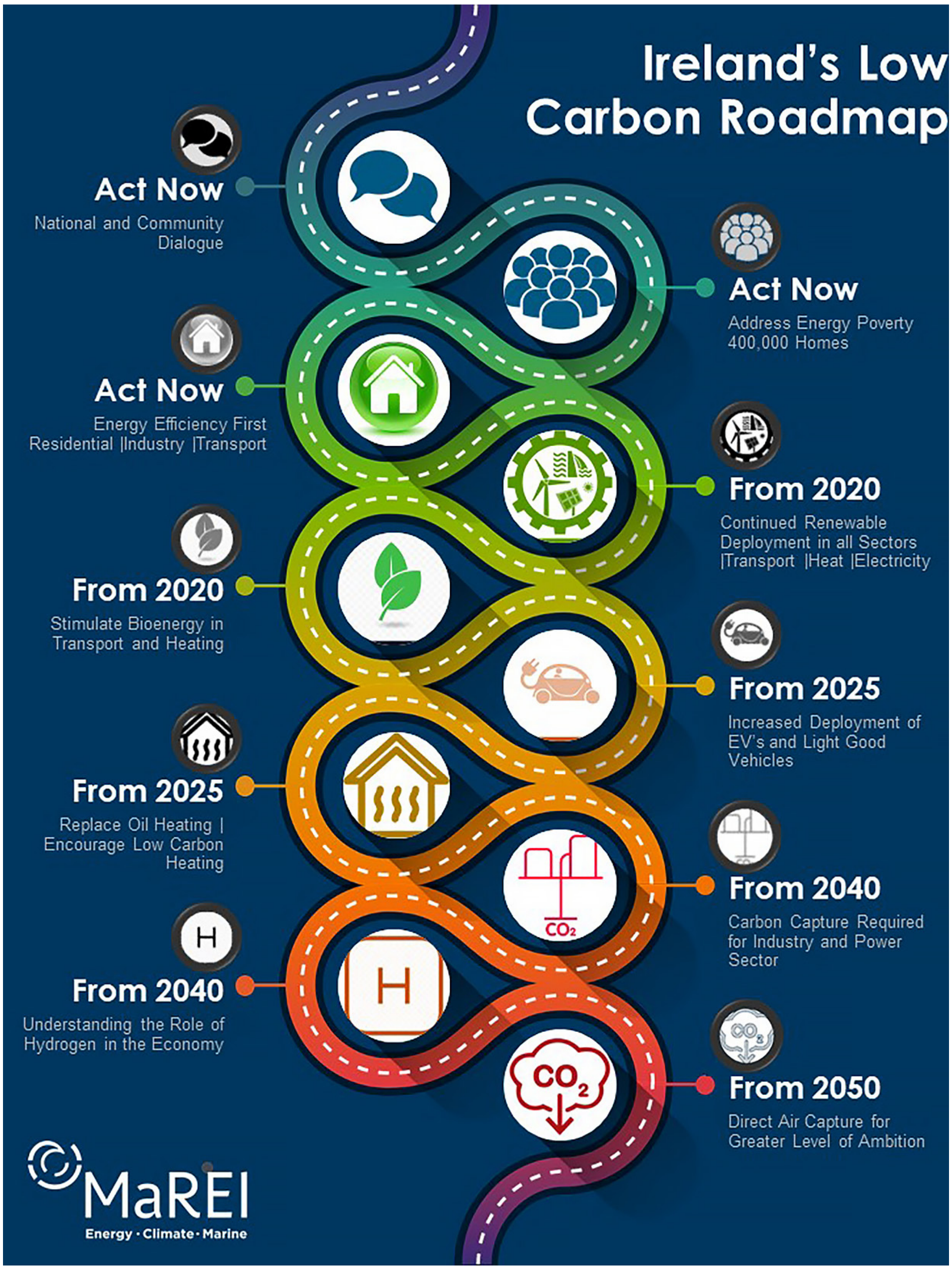


Figure 6.1. The MaREI Irish TIMES roadmap for Ireland's energy transition to a zero carbon future.

2. *Recommendation 2*. The roles and costs of hydrogen and new synthetic fuels in the future Irish economy require greater understanding.
3. *Recommendation 3*. (Solid, liquid and gaseous) bioenergy has a significant potential contribution to make to Ireland’s low carbon future, in particular for heating and transport. This requires significant policy consideration.
4. *Recommendation 4*. The future role of CO_2 removal technologies in Ireland, including CCS, requires further analysis.
5. *Recommendation 5*. This project shows the radical changes required to transition towards a low and net zero GHG emissions future for Ireland. A significant increase in research on the societal dimensions of these changes is urgently required.

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Abbreviations

BECCS	Bioenergy carbon capture and storage
CCS	Carbon capture and storage
EPA	Environmental Protection Agency
ESRI	Economic and Social Research Institute
ETS	Emissions Trading System
ETSAP	Energy Technology Systems Analysis Program
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
IAM	Integrated assessment model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MACC	Marginal abatement cost curve
MaREI	Marine and Renewable Energy Ireland
MSA	Macro Stand Alone
NDC	Nationally Determined Contribution
NMP	National Mitigation Plan
PRIMES	Price-Induced Market Equilibrium System
RES-E	Renewable energy sources for electricity
SEAI	Sustainable Energy Authority of Ireland
SFI	Science Foundation Ireland
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
TRAM	Technical Research and Modelling Group
UCC	University College Cork

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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The Role of Energy Technology in Climate Mitigation in Ireland: Irish TIMES Phase 3

Authors: Brian Ó Gallachóir, Paul Deane, James Glynn, Fionn Rogan

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying Pressures

The use of fossil fuels for energy, poor land management and agriculture practices are driving the unequivocal warming of our climate system. The Paris Agreement, reached in 2015, was very significant in terms of the global politically agreed ambition regarding climate action (i.e. pursuing efforts to limit the temperature increase to well below 2°C and making efforts to limit warming to 1.5°C above pre-industrial levels). The remaining carbon budget to stay below 1.5°C by 2100 with a greater than 50% probability is estimated at 200 GtCO2–700 GtCO2. The cumulative carbon budgets for Ireland utilised in this analysis range from 766 MtCO2 to 128 MtCO2 from 2015 to the end of the time horizon (2070). They are derived from the Irish population share of 0.064% of the global population and the same 0.064% share of the remaining global carbon budgets. These carbon budgets relate to a 66% probability of achieving a 2°C limit, to a 50% probability of reaching a 1.5°C limit, and are chosen to span the technically feasible range of mitigation options for Ireland.

Informing Policy

This project enabled the MaREI Centre for Energy, Climate and Marine to evaluate the role of energy technology in climate mitigation in Ireland. A key development in Irish TIMES, Ireland's only fully integrated long-term energy systems optimisation model, was the capacity to provide net zero emissions scenarios for Ireland that are considered to be consistent with the Paris Agreement temperature goals. MaREI used the models developed in this project to inform national engagement on EU greenhouse gas (GHG) emissions target setting in 2014. It also informed the 2015 White Paper on Energy, Ireland's first National Mitigation Plan in 2017 and the government's Climate Action Plan in 2019. Regarding the Climate Action Plan, this analysis focused on increasing Ireland's long-term ambition to 2050 beyond the 80% reduction target for CO2 and on how this aligns with Ireland's target under European Union legislation for GHG emissions reduction by 2030.

Developing Solutions

This report focuses on the role of clean technologies in all sectors of the Irish economy and highlights that no silver bullets exist. Many technologies are required across all sectors. Energy efficiency is a resilient technology choice and is an enabler of low carbon choices. Continued deployment of renewables in all modes of energy (electricity, heat and transport) is required, in particular the continued deployment of bioenergy in the heating and transport sectors. The roles of energy efficiency, the growth of electrification and the increase in renewable electricity are reflected in the political and media discourse on climate action in Ireland. However, the potential contribution from bioenergy and negative emissions technologies reflected in this analysis are still largely ignored. The roles and costs of hydrogen and new synthetic fuels in the future Irish energy systems require greater understanding.

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