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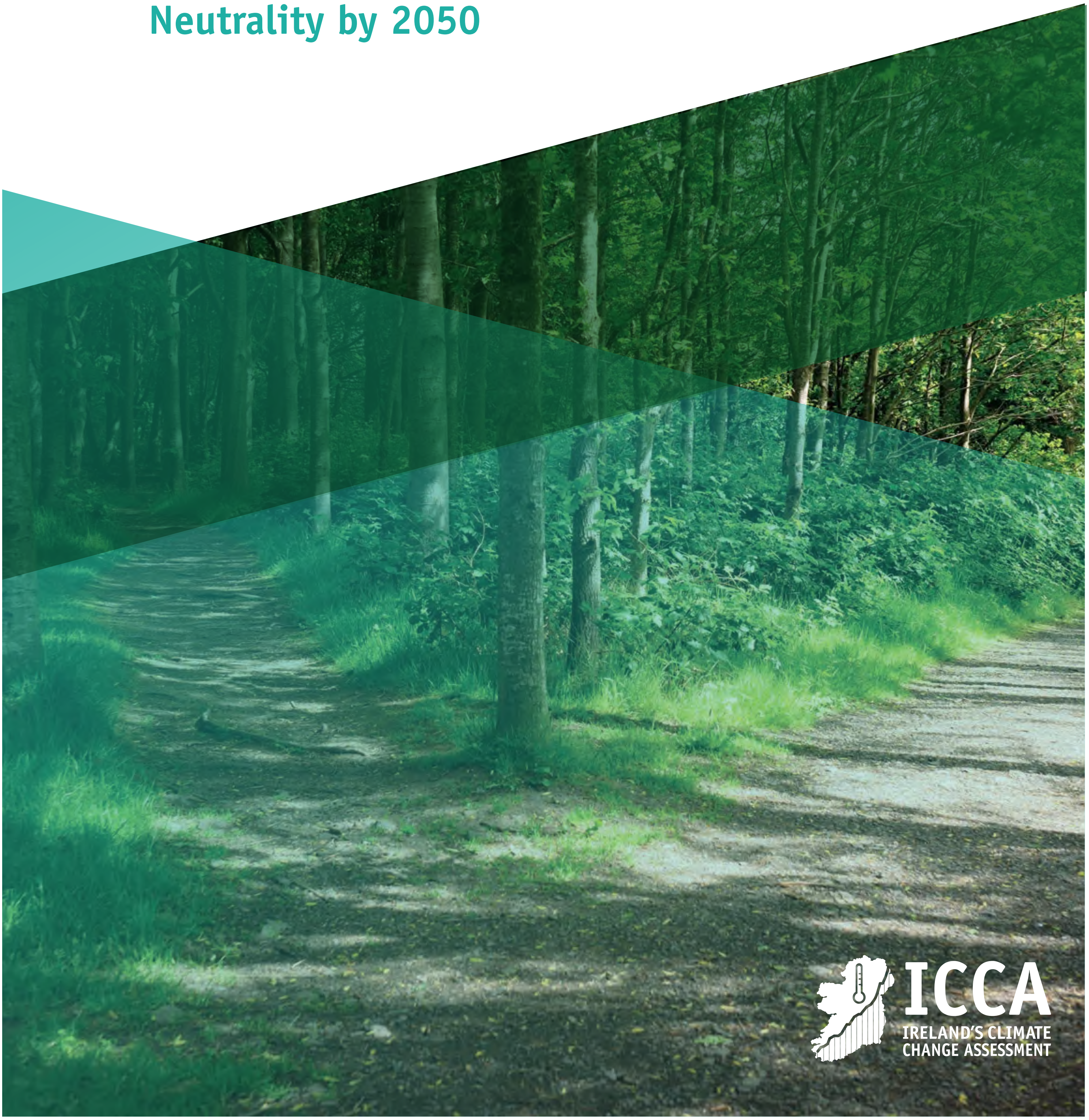
IRELAND'S CLIMATE CHANGE ASSESSMENT

Volume 2: Achieving Climate Neutrality by 2050



Ireland's Climate Change Assessment 2023

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IRELAND'S CLIMATE CHANGE ASSESSMENT

Volume 2: Achieving Climate Neutrality by 2050

ICCA
IRELAND'S CLIMATE CHANGE ASSESSMENT

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Foreword

This is the first Ireland's Climate Change Assessment (ICCA) and is a major contribution to the national dialogue and engagement on climate change. It tells us what is known about climate change and Ireland. It also provides key insights on gaps in our knowledge. The development of ICCA was modelled on the work of the Intergovernmental Panel on Climate Change and the Sixth Assessment Cycle, completed in 2023, with the use of and localisation of its information for Ireland.

ICCA will support the national response to climate change, ensuring that it is informed by the best available science. It also points to how and where that science can be improved through further investments in innovation, in research and in systematic observations. These collectively form the essential backbone of the science and data required to understand how Ireland is being impacted by and responding to the climate change challenge.

The full Assessment has been developed through a co-creation process between leading academics in Ireland and officials from across state agencies and government departments. Funding was provided by the Environmental Protection Agency, Sustainable Energy Authority of Ireland, Science Foundation Ireland and Department of Transport. The process was collaborative, involving mutual development and agreement of the scope, preparation and review of drafts, wider stakeholder consultation through a series of workshops and meetings, and a detailed sign-off process.

We see the publication of ICCA as a real innovation for Ireland and as a resource for understanding climate change in an Irish context across the underlying science, mitigation and adaptation measures, and opportunities. It is a starting point for further dialogue on the findings and their utility for policymakers, practitioners, researchers, research funders and people. This engagement phase should continue far beyond the publication of this Assessment and support climate action in Ireland.

Dr Eimear Cotter
Director of the Office of Evidence and Assessment, EPA
Chair of the ICCA Steering Committee

"Each degree matters, each year matters, and each decision matters: not acting today is adding to the burden of the next generations .... Limiting global warming to 1.5°C is not impossible but requires strong and immediate policies."

Valérie Masson-Delmotte,
Co-chair of working Group I of the IPCC
(8 October 2018 – French Senate intervention)

Summary for Policymakers

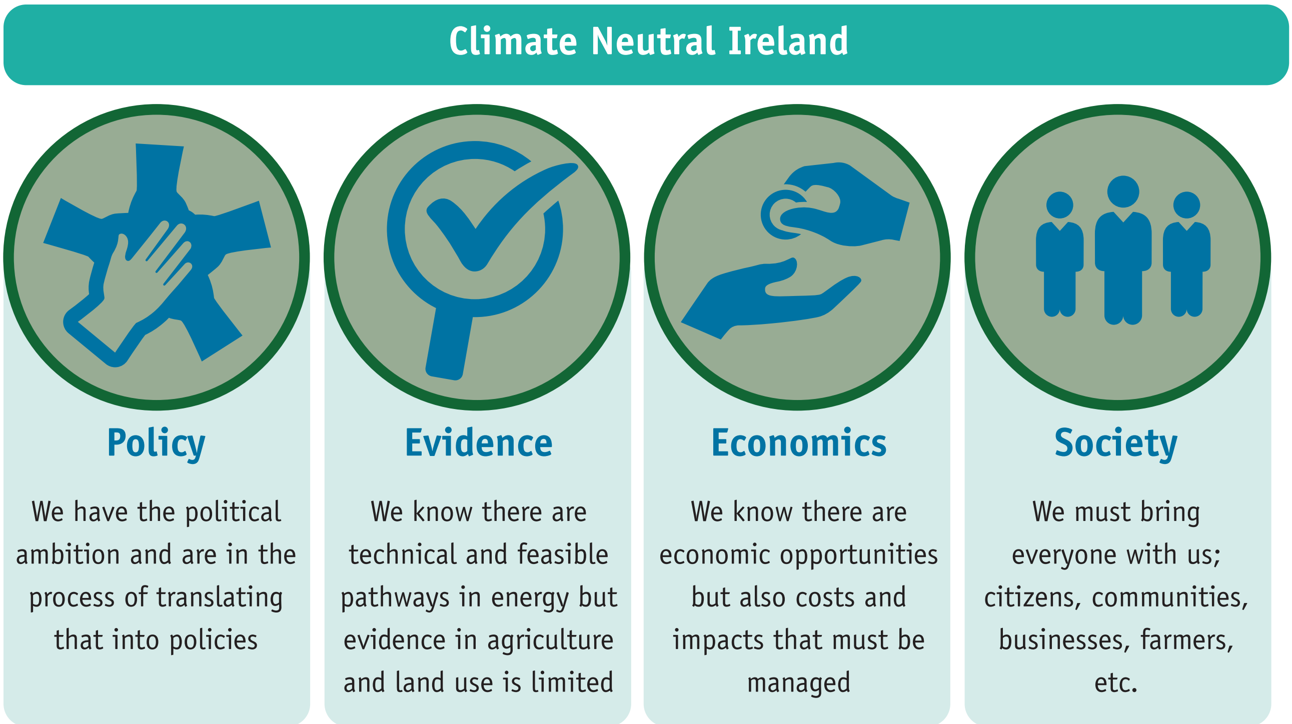

Figure SPM.1 Ireland's strategy towards climate neutrality[1].

A. The starting point: greenhouse gas emissions and climate policy in Ireland

Since the Industrial Revolution, enhanced levels of atmospheric greenhouse gases, particularly carbon dioxide, have changed the Earth's energy balance, resulting in less heat being lost to space. This is causing global warming, which is observed as increased global average temperatures, changes in precipitation patterns, mean sea level rise and changes in the character of weather extremes.

Greenhouse gases are composed of several different heat-trapping gases, with carbon dioxide being the largest and most important contributor to climate change. Methane, nitrous oxide, industrial gases and ozone are also important greenhouse gases. The influence of these greenhouse gases and other climate forcers (e.g. aerosols) on the Earth's energy balance are detailed in Ireland's Climate Change Assessment (ICCA) Volume 1.

To address climate change, both Ireland and the EU are Parties to the United Nations Framework Convention on Climate Change and the 2015 Paris Agreement. The Paris Agreement entered its implementation phase in 2020 as the global framework for addressing climate change. The Paris Agreement established goals relating to temperature, climate resilience and financial flows. Specifically, these are to hold the global average temperature increase to well below 2°C and pursue efforts to limit the increase to 1.5°C. {Chapter 1}

Ireland and other Parties to the Paris Agreement have committed to collectively reaching a global 'balance' of greenhouse gas emissions and removals during the second half of this century on the basis of equity, reflecting common but differentiated responsibility in light of different national circumstances. Ireland's commitments have been agreed with EU partners and submitted as a collective EU nationally determined contribution under the Paris Agreement. These are framed by national long-term emissions reductions strategies.

[1] There are different interpretations of the term climate neutrality. The EU Climate Law aligns it with achieving net zero greenhouse gas emissions by 2050. The Climate Action and Low Carbon Amendment Act 2021 interprets a "climate neutral economy" as a "sustainable economy and society where greenhouse gas emissions are balanced or exceeded by the removal of greenhouse gases". This is the interpretation used in this report that draws on the long-term mitigation analysis published for Ireland. Evolving interpretations of climate neutrality include adopting separate approaches for long- and short-lived greenhouse gas emissions and the need to include the roles of short-lived climate forcers.

Collective global progress in achievement of the goals of the Paris Agreement and the scale of stated collective ambition are assessed under the Paris Agreement global stocktake every 5 years, starting from 2023.

Ireland is ranked second highest across the EU when all greenhouse gas emissions are considered on a per person basis. Compared with other EU Member States, Ireland has higher than average emissions of methane and nitrous oxide because we have the highest agriculture emissions contribution to our national total emissions. A similar pattern can be seen in New Zealand, where agriculture is also an important part of the economy.

Ireland's greenhouse gas emissions increased by 29% in the period from 1990 to 2001, the year in which emissions peaked. In the period since 2001, Ireland's emissions have reduced by 14%.

A.1. Ireland has made limited progress in reducing greenhouse gas emissions but there is a very long way to go

Ireland's greenhouse gas emissions peaked in 2001. Greenhouse gas emissions per capita have decreased from 18 tonnes in 2001 to 12 tonnes per person in 2021. Carbon dioxide is the most significant contributor to the greenhouse gas emissions in Ireland. Ireland's energy system is heavily dependent (86%) on fossil fuels. Carbon dioxide emissions in the transport sector have doubled since 1990. Ireland's large livestock population is the main driver of methane and nitrous oxide emissions, the second and third most significant contributors to greenhouse gas emissions in Ireland. Land use, land use change and forestry (LULUCF) in Ireland is a source of greenhouse gas emissions rather than a sink. {Chapter 2}

A1.1	Having peaked in 2001, Ireland's greenhouse gas emissions reduced in all sectors except agriculture[2]. In 2021, Ireland's total greenhouse gas emissions are estimated to be 62 million tonnes carbon dioxide equivalent[3] (69 million tonnes including LULUCF[4]), which is approximately 11% higher than emissions in 1990 and 14% lower than emissions in 2001. Greenhouse gas emissions per capita increased from 16 tonnes carbon dioxide equivalent per person in 1990 to 18 tonnes in 2001, and reduced to 12 tonnes per person in 2021.
A1.2	Carbon dioxide is the most significant contributor to greenhouse gas emissions in Ireland at 60.5% of total greenhouse gas emissions excluding LULUCF. The electricity and transport sectors were responsible for 27% and 29% of total carbon dioxide emissions (excluding LULUCF) in 2021, respectively. There was a 14% increase in carbon dioxide emissions from 1990 to 2021, due to a doubling of emissions from fossil fuel combustion in the transport sector over the period. Ireland's energy system is heavily dependent (86%) on fossil fuels.
A1.3	Methane is the second most significant contributor to greenhouse gas emissions in Ireland (28.4% of total greenhouse gas emissions excluding LULUCF) and is due to the large livestock population. Emissions of methane increased from 1990, reaching a peak in 1998, then decreased due to falling livestock numbers and returned to near record levels again in 2021. The main contributor to the methane trend is the agriculture sector, and in 2021 this sector accounted for 94% of the methane emissions.
A1.4	Nitrous oxide emissions (10.3% of total greenhouse gas emissions excluding LULUCF) increased during the 1990s to peak in 1998, reflecting the increased use of synthetic fertilisers and increased amounts of animal manures associated with increasing animal numbers. Emissions subsequently showed a downwards trend followed by an increase in the period 2015–2021, as the dairy sector expanded and nitrogenous fertiliser use increased.

2 EPA (2023). Ireland's National Inventory Report 2023: Greenhouse Gas Emissions 1990–2021.

3 Greenhouse gases other than carbon dioxide (i.e. methane, nitrous oxide and fluorinated gases) can be aggregated as carbon dioxide equivalents using their global warming potentials from the Intergovernmental Panel on Climate Change Fifth Assessment Report. Here, the global warming potential of a gas is a measure of the cumulative warming over a specified time, usually 100 years, by a unit mass of this gas. More detail on global warming potential is available in ICCA Volume 1.

4 Unless stated, all national greenhouse gas numbers exclude the LULUCF sector, which covers the following categories: forest land, cropland, grassland, wetlands, settlements, other land and harvested wood products. This sector has historically not been included in the published national emission totals unless explicitly stated but is reported in submissions to the EU and UN. Its recent inclusion in the published national emission totals reflects national policy, specifically arising from the inclusion of LULUCF in Ireland's 2030 greenhouse gas emission reduction target and in carbon budgets. This sector is a net source of greenhouse gas emissions.

A.2. Irish and European climate ambition has significantly increased since 2019

Climate policy at national and EU and UN levels has evolved rapidly since the adoption of the Paris Agreement. Ireland has established a statutory target for a 51% reduction in total greenhouse gas emissions (including LULUCF) by 2030, compared with 2018 and has legislated for a long-term national climate objective of climate neutrality by 2050 at the latest. The European Climate Law establishes a legislative framework for the EU to become climate neutral by 2050 and sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels. {Chapter 2}

A2.1 The Climate Action and Low Carbon Development Act (Amendment) 2021 (Climate Act 2021) establishes a target for a 51% reduction in total greenhouse gas emissions (including LULUCF) by 2030, compared with 2018, and a long-term national climate objective of climate neutrality by 2050 at the latest. The Climate Act also provides for the establishment of carbon budgets[5] as a legislative framework for achieving Ireland's climate ambition. The 51% target, relative to 2018, is the primary constraint on carbon budgets over the course of the first two budget periods, ending on 31 December 2030.

A2.2 The European Climate Law establishes a legislative framework for the EU to become climate neutral by 2050. This enshrines the European Green Deal, which provides for investing in green technologies and protecting the natural environment in order to achieve net zero greenhouse gas emissions by 2050. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels, under the EU Fit for 55 legislative package[6]. {Chapter 2}

Ireland's 2030 target under the EU's Effort Sharing Regulation is to limit its greenhouse gas emissions by at least 42% by 2030 in the areas mainly outside electricity generation[7]. The 42% reduction defines the trajectory with annual binding emission limits over the period to 2030. Ireland has access to EU-wide flexibilities to allow for a fair and cost-efficient achievement of the target. These flexibilities include intra-EU trading of Member State emissions allowances, the use of EU Emissions Trading System allowances and credit from action undertaken in the LULUCF sector. {Chapter 2}

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5 Ireland's carbon budgets provide a maximum 5-yearly total for greenhouse gas emissions based on all emissions aggregated in terms of carbon dioxide equivalents determined by their 100-year global warming potential as provided in the Intergovernmental Panel on Climate Change Fifth Assessment Report.

6 The EU Fit for 55 legislative package has been submitted to the United Nations Framework Convention on Climate Change as the EU nationally declared contribution to the Paris Agreement.

7 Greenhouse gas emissions reductions in the electricity sector, large industry and intra-EU aviation are legislated for separately under the EU Emissions Trading System.

8 EPA (2023). *Ireland's National Inventory Report 2023: Greenhouse Gas Emissions 1990–2021*.

9 EPA (2023). *Ireland's Greenhouse Gas Emissions Projections 2022–2040.*

A.3. Additional policies and actions are required to meet legally binding targets

Large-scale and immediate greenhouse gas emissions reductions are needed across energy, agriculture and land use to meet Ireland's legally binding targets. Ireland has the high-level political climate ambition, and the necessary technologies, but there is a disconnect between this and the delivery of political, financial, societal and industry climate action. {Chapter 2}

A3.1	Greenhouse gas emission estimates for 2021 and 2022 indicate that 47% of Ireland's first carbon budget has been emitted within 40% of the budget time frame[8].
A3.2	Ireland's first two carbon budgets (2021–2030) under the Climate Act 2021 are projected[9] to be exceeded by a significant margin of between 24% (117MtCO_2-eq) and 34% (170MtCO_2-eq). In addition, any shortfall in the first carbon budget will be carried over to the second carbon budget period.
A3.3	Current polices are not sufficient to meet the legally binding national carbon budgets for 2021–2025 and 2025–2030.

A.4 Achieving Ireland's climate goals will be challenging and will need to take account of our global responsibilities

A4.1	Achieving net zero carbon dioxide emissions by 2050 requires significant and unprecedented changes to our energy system. In addition, implementation of emissions mitigation strategies across agriculture and land use sectors, including diversification, has not been achieved to date. Achieving net zero greenhouse gas emissions (or achieving climate neutrality[10]) by 2050 is very challenging.
A4.2	To date, climate mitigation research has not identified technically feasible scenarios in which Ireland can remain within its population-weighted share of the remaining global carbon budget for 1.5°C. It is Ireland's cumulative emissions in the period to 2050, rather than meeting net zero by 2050, that determine Ireland's contribution to climate change.
A4.3	Current energy systems modelling shows that achieving net zero carbon dioxide emissions by 2050 requires unprecedented changes and in itself is not sufficient to achieve climate neutrality. {Chapter 3}
A4.4	Estimating how to equitably distribute remaining global carbon budgets has legal, ethical and practical dimensions. Addressing such equity issues is central to implementation of the Paris Agreement and will be considered by governments during the 5-yearly global stocktake of climate action that begins in 2023.
A4.5	The energy scenarios modelled to date as being technically feasible exceed Ireland's population-weighted share of the remaining 1.5°C cumulative emissions trajectories.
A4.6	Apportioning the global carbon budget using different approaches informed by other ethical principles (such as ability to pay or historical emissions) will produce different estimates of equitable share.
A4.7	Modelling of agriculture emissions and the projected impact of mitigation measures indicates that there are a range of measures that can be taken. {Chapter 6}
A4.8	Significant implementation of mitigation measures, including diversification, has not been achieved in Ireland to date, making the achievement of climate neutrality more challenging.
A4.9	Research on what is required to achieve climate neutrality across the agriculture and land use sectors is at an early stage and more analysis on what levels of agriculture emissions can feasibly be balanced with land use removals is urgently needed. {Chapter 7}

[10] This volume interprets achieving climate neutrality by 2050 as achieving net zero greenhouse gas emissions in Ireland by 2050. The Climate Act 2021 interprets a "climate neutral economy" as a "sustainable economy and society where greenhouse gas emissions are balanced or exceeded by the removal of greenhouse gases".

B. The options to achieve climate neutrality: future energy system and greenhouse gas emission choices

In its Sixth Assessment Report, the Intergovernmental Panel on Climate Change highlighted the existence of technological, political and economic solutions to achieve rapid and widespread emission reductions. Projected cumulative future carbon dioxide emissions from current and planned energy infrastructures worldwide would, over their lifetime and without additional abatement, likely exceed the cumulative global budget for limiting warming to 1.5°C.

Similarly, studies suggest that Ireland's future energy-related emissions would exceed a per capita share of the global 1.5°C budget, without additional unprecedented carbon dioxide emission reductions and/or reliance on large-scale carbon dioxide removals.

Large-scale and immediate greenhouse gas emissions reductions are needed across the whole energy system (electricity, heat and transport), agriculture and land use to meet Ireland's legally binding targets. The range of technical mitigation options available in agriculture are still in nascent stages (requiring more research and investments) than those within the energy sector. There are a growing number of options for mitigating methane and nitrous oxide emissions in agriculture that are at different stages of development. Although there is international research on how reductions in energy and livestock challenge the current economic growth paradigm, this research is limited to date in Ireland.

B.1. Features of net zero carbon dioxide energy systems

There are well-established 'no-regret options' that must happen now, which can get us most of the way to net zero carbon dioxide emissions. Beyond that, there are 'future energy choices' relating to the scale and magnitude of technologies that will help get us all the way. Energy demand reduction is the replacement of fossil fuels with renewable energy is necessary, but carbon dioxide removal from the atmosphere is also required. Electrification of heating and transport is necessary but not sufficient to achieve a net zero energy system. Ireland will need new energy carriers in the form of bioenergy or hydrogen for heavy transport and high-grade heat in industry, and should also look at alternatives such as district heating for urban areas. {Chapters 3, 4, 5}

B1.1	There are well-established 'no-regret options' that must happen now, which can get us most of the way. These are **demand reduction** (e.g. through energy efficiency and reduced consumption), **electrification** (e.g. electric vehicles and heat pumps), **deployment of market-ready renewables** (e.g. wind and solar) and **low-carbon heating options** (e.g. district heating).
B1.2	Beyond that, there are **future energy choices** relating to the scale and magnitude of technologies that will help get us to net zero emissions. These technologies include hydrogen, carbon capture and storage, nuclear energy[11] and electrofuels. While the scale and mix of these specific technologies are currently unclear, it should not be and is not a barrier to action.
B1.3	A benefit of a net zero energy system is **a significant reduction in the import of fossil fuels into Ireland** to meet our energy needs, from 70% today to less than 5% in the future, according to the literature to date. There are many additional societal co-benefits, including human health and air quality.
B1.4	Figure SPM.2 provides one indicative pathway for Ireland to achieve a net zero energy system by 2050.

[11] Developing nuclear energy or carbon storage would require legislative changes.

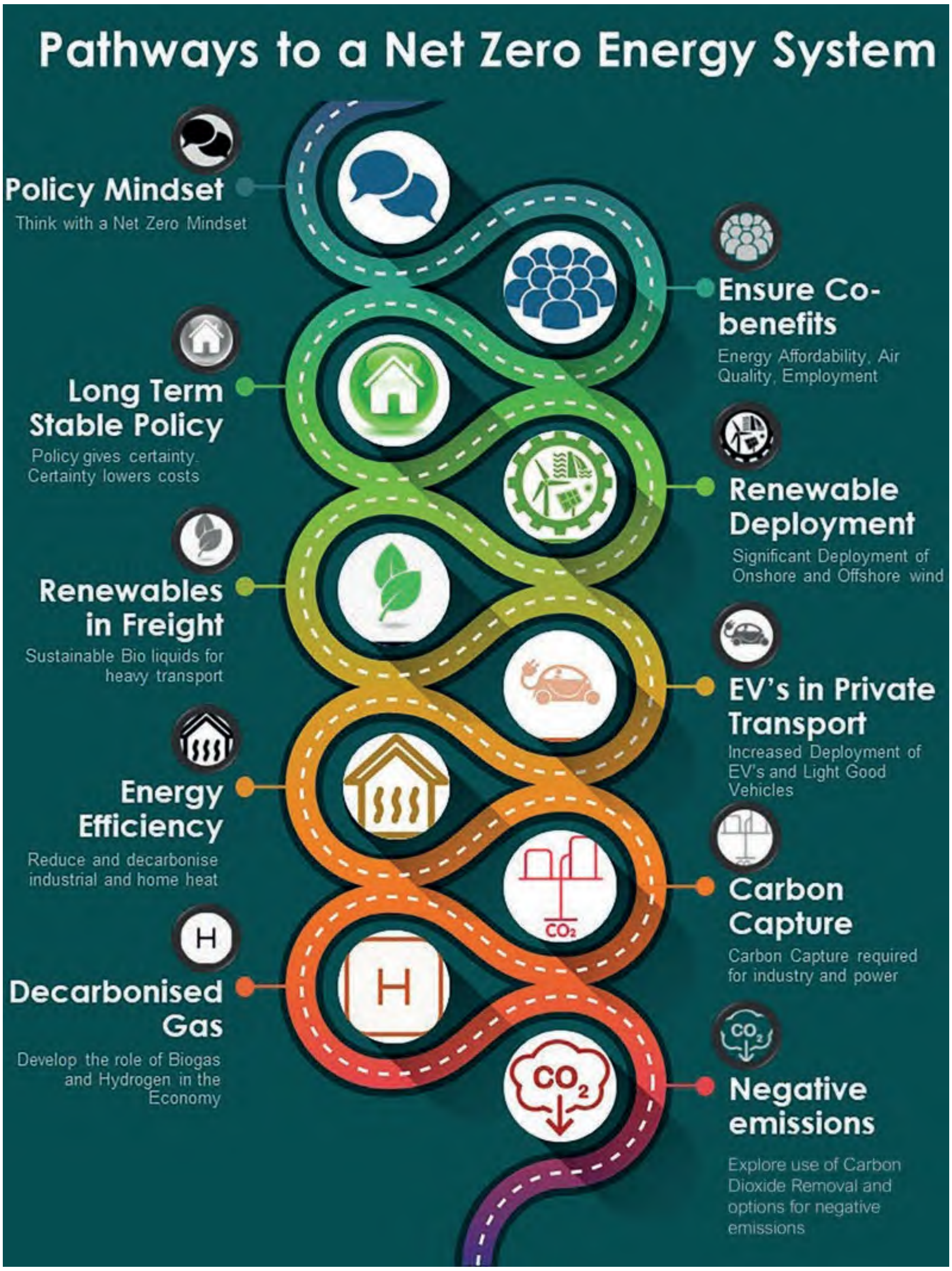


Figure SPM.2 An indicative pathway to achieve a net zero energy system in Ireland. (Source: MaREI Centre)

B.2. A wide range of interventions is needed to transform Ireland's energy system away from fossil fuels

Significant reductions if not complete elimination in fossil fuel usage is required. Avoid–shift–improve is a useful framework emanating from mobility research that should be applied across all sectors. Transformative system-wide changes across the energy system can deliver multiple co-benefits, including in the areas of health, air pollution and energy justice.

B2.1	Significant reductions if not complete elimination in fossil fuel usage is required. Avoid–shift–improve[12] provides a framework to deliver the necessary transformations across all sectors, including industry, transport, residential and services sectors.
B2.2	Planning compact development within urban areas will be important to reduce greenhouse gas emissions associated with land use change and urban sprawl. This would also help in reducing emissions in transport in particular, but also in reducing infrastructural costs and losses in biodiversity and vegetated land.
B2.3	Reducing emissions in homes is essential. Where homes also use solid fuels as their main fuel source, and these can be replaced with low-carbon alternatives, this can have the added benefit of improving local air quality.
B2.4	Retrofitting the homes of those experiencing energy poverty should be a priority, as it is crucial for a just transition. The share of households experiencing energy poverty has grown from 16% in 2013 to an estimated 40% at the end of 2022: almost double its previously recorded high of 23% in 1994/95.

B.3. Ireland needs to transition to a renewables future but will also need carbon dioxide removals

Wind energy and solar photovoltaics can provide the backbone of Ireland's future electricity system, but additional options are also required to ensure security of supply. Ireland's renewables success to date has been with renewable electricity (primarily wind energy, which increased from 36.4% of Ireland's electricity in 2021 to 36.8% in 2022). Renewable heating and transport are lagging far behind. Bioenergy, other renewables and hydrogen will be needed in sectors not currently suited to electrification. The literature to date also concludes that some levels of carbon capture, storage and removal across the economy will likely be needed.

B3.1	Offshore/onshore wind and solar photovoltaics can provide the backbone of Ireland's future electricity system. However, it will not be enough. To ensure grid stability and security of supply, the system will also require other options, such as increased interconnection, demand flexibility, storage and zero emission back-up generation. {Chapter 4}
B3.2	Alternatives such as bioenergy, other renewables and hydrogen will be needed in sectors not currently suited to electrification, such as heavy transport and industry, and to balance a grid based on variable renewable electricity technologies. These require further investigation. {Chapter 4}
B3.3	Renewable energy can increasingly provide our future energy needs but will need to be complemented with carbon dioxide removals to achieve a net zero energy system in hard-to-abate sectors. The literature to date concludes that some levels of carbon capture, storage and removal across the economy will likely be needed. {Chapter 4}

[12] Avoid–shift–improve is a demand-side focused approach designed to improve the efficiency of the transport system. This approach would enable significant reductions in greenhouse gas emissions and reduced energy consumption and congestion and would create a more liveable urban infrastructure.

B.4. Significant mitigation is needed in agriculture, Ireland's largest sectoral source of greenhouse gas emissions

Ireland has higher than average emissions of methane and nitrous oxide within the EU because of its large livestock sector. Innovations in the development of feed additives to inhibit enteric methane protection are under way and the use of protected urea to reduce nitrous oxide emissions is still in the early stages of implementation. There is currently a key evidence gap in how to achieve climate neutrality in agriculture. Low-emission fertilisers, optimal use of slurry and planting legumes to improve nitrogen use efficiency are recommended. Optimal use of no-regret livestock management measures, such as increasing the dairy Economic Breeding Index, improving herd genetics, improving animal health and promoting efficient feeding strategies, will help in reducing greenhouse gas emissions. Diversification within the sector will be necessary to achieve deep emission reductions. It is very important because this can reduce livestock numbers and enable different land use strategies, such as bioenergy and agroforestry.

B4.1	Beef and dairy farming contribute most significantly to agriculture emissions (in particular methane and nitrous oxide). Innovations such as feed additives to reduce biogenic methane and use of protected urea to reduce nitrous oxide are still in early stages of implementation in Ireland. {Chapter 6}
B4.2	There is a lack of evidence in Ireland on achieving climate neutrality. The literature suggests that a precautionary approach would require adoption of mitigation measures. To reduce nitrous oxide emissions, no-regret mitigation measures include changing to low-emission fertiliser types and optimal use of slurry and legumes to increase nitrogen use efficiency. No-regret mitigation measures for methane include increasing the dairy Economic Breeding Index, beef genomics, improved animal health, extending the grazing season and use of sexed semen within beef and dairy sectors. {Chapter 6}
B4.3	Encouraging and incentivising diversification strategies within the sector are important because reductions in livestock numbers and adopting different land use strategies and bioenergy will likely be necessary to achieve and maintain deep emission cuts. {Chapter 7}

B.5. Land use, land use change and forestry in Ireland is a net source of emissions rather than a net sink

Different combinations of afforestation, rewetting of organic soils and enhancing carbon sequestration in mineral soils are the primary means to achieve net zero emissions within LULUCF. Additional analysis of drainage and the nutrient status of peat soils would help in substantiating the total potential reduced emissions and increased removals that can be achieved via improved land management.

B5.1	Research on LULUCF suggests that the primary means to get to net zero for this sector is through unprecedented rates of afforestation, rewetting in organic soils (including water table management and reduced management intensity), enhanced carbon sequestration in mineral soils and peatland rehabilitation. {Chapter 6}
B5.2	More analysis and interpretation are required within LULUCF, especially in improving the greenhouse gas emissions inventory in Ireland, Europe and globally. This includes increasing use of observational data from soil flux towers and atmospheric sites. Additional analysis of drainage and the nutrient status of peat soils (including agricultural and forested land) would help in understanding the total potential reduced emissions and increased removals that could be achieved through land management. {Chapter 6}

B.6. Common features of climate-neutral pathways

This report interprets 'achieving climate neutrality by 2050' to mean achieving net zero greenhouse gas emissions by 2050. There are no published climate neutrality studies or pathways for Ireland that cover all sources of greenhouse gas emissions in sufficient detail[13]. There are nine existing studies of net zero pathways for Ireland: six covering the energy system and three on agriculture, forestry and land use. Global mitigation pathways show carbon dioxide emissions reaching net zero 10–15 years before other greenhouse gas emissions, and this implies that Ireland should reach net zero carbon dioxide emissions between 2035 and 2040. After reaching net zero carbon dioxide, the energy system would require further negative emissions balance from residual emissions such as methane, nitrous oxide and industrial gases. {Chapter 7}

B6.1	Global mitigation pathways show carbon dioxide emissions going to net zero 10–15 years before other greenhouse gas emissions. Applying that to Ireland, the goal of climate neutrality by 2050 implies reaching net zero carbon dioxide emissions at latest between 2035 and 2040.
B6.2	After reaching net zero carbon dioxide, the energy system will likely need to provide further negative emissions to balance residual greenhouse gas emissions (including industrial process, methane and nitrous oxide emissions).
B6.3	It is not possible for this assessment to provide a clear pathway for climate neutrality or quantify the extent of negative emissions required, as the evidence is currently lacking.
B6.4	Addressing the knowledge gaps including an integrated assessment of agriculture, energy and land use is needed. {Chapter 9}

[13] There is also one study that shows scenarios for the three main greenhouse gases (carbon dioxide, methane and nitrous oxide) but it lacks the necessary sectoral details.

C. Key insights for policy {Chapter 9}

C.1	**Climate-neutral pathways for Ireland** There is a significant gap in the literature available for climate-neutral pathways in Ireland. Although there have been studies to incorporate agriculture within the energy models, the mitigation options explored do not achieve net zero. The knowledge gaps, especially in the LULUCF sector, make this more challenging.
C.2	**Need for deep emission reductions within the agriculture and land use sectors** Deep emission reductions within the agriculture and land use sectors is a critical aspect of Ireland's efforts to mitigate climate change and transition to a low-carbon economy. The research on LULUCF suggests that the primary means to get to net zero for this sector is through unprecedent rates of afforestation and rewetting of organic soil along with a significant reduction in herd numbers. The majority of the precautionary mitigation options available in Ireland are still in the early implementation stages, and there is an urgent need for Ireland to explore various diversification strategies to enable deep mitigation.
C.3	**The energy system post 2030** Policies tailored to suit different stages of technology development are very critical for achieving a net zero energy system. Established technologies such as wind energy, solar photovoltaics and bioenergy will be key in short-term emission reduction targets (i.e. 2030), whereas offshore wind infrastructure is expected to be the backbone of future energy systems. This can only be achieved with appropriate support schemes, regulation and investments for synergistic growth of offshore wind and other renewable technologies. Future energy choices post 2030 need greater exploration to plan for the required transition.
C.4	**Ex-post evaluating of policies and measures** A retrospective evaluation of why Ireland has not yet achieved significant emission reductions could provide lessons to guide in designing future mitigation strategies. Also, careful evaluation of existing government-aided support schemes for fair distribution among individuals and businesses is also required.
C.5	**Model development priorities** Further analysis is needed to deliver emissions and removals data at subnational levels, e.g. county and local levels. Mappings of energy use and associated emissions can support local authority planning. There is also a need for the industry and services sectors to undertake more detailed analysis and for transport and residential emissions to receive a broader policy analysis, i.e. beyond private car transport and residential retrofitting.
C.6	**Enhancing public participation** Public engagement and participation in development and implementation of transition management is essential. Further research is necessary to improve the translation of Citizens' Assembly recommendations and outcomes from subsequent engagement processes into policy, to enhance local deliberative processes, and to inform a just transition that protects and includes vulnerable groups in the shift to a climate-neutral society.
C.7	**Enabling climate and energy financing** Further analysis on the impact of financial incentives and drivers, including carbon pricing on behaviour, investment patterns in low-carbon technologies and the use of revenue to drive an efficient, just transition, is necessary. The use of financing, fiscal instruments and governance of climate mitigation is also a critical area that warrants more attention.

C.8	**Alternative economic paradigm** Understanding the potential impacts of alternative economic models, such as degrowth, in the Irish context is crucial for developing sustainable policies and strategies. Understanding the implications and potential impacts of these models, as well as the necessary transformations, can inform policy development and contribute to a more sustainable and resilient future.
C.9	**Bringing mitigation and adaptation actions together** There is a need for a systems approach that integrates both mitigation and adaptation in Ireland's policy responses to climate change. Further research is necessary to explore the co-benefits and future risks, and the resilience of transition pathways, as well as those associated with specific measures. Integrated alignment of planning and implementation of climate actions should support rapid progress in addressing climate change challenges.
C.10	**Deep institutional innovation** There is a need to move beyond a narrow focus on carbon dioxide abatement and consider broader societal and environmental impacts when assessing policies. By considering a wider range of metrics and reimagining institutions, policymakers can make more informed decisions that address the complexities of sustainability, ethics and effectiveness in a holistic manner.

D. Key recommendations for research

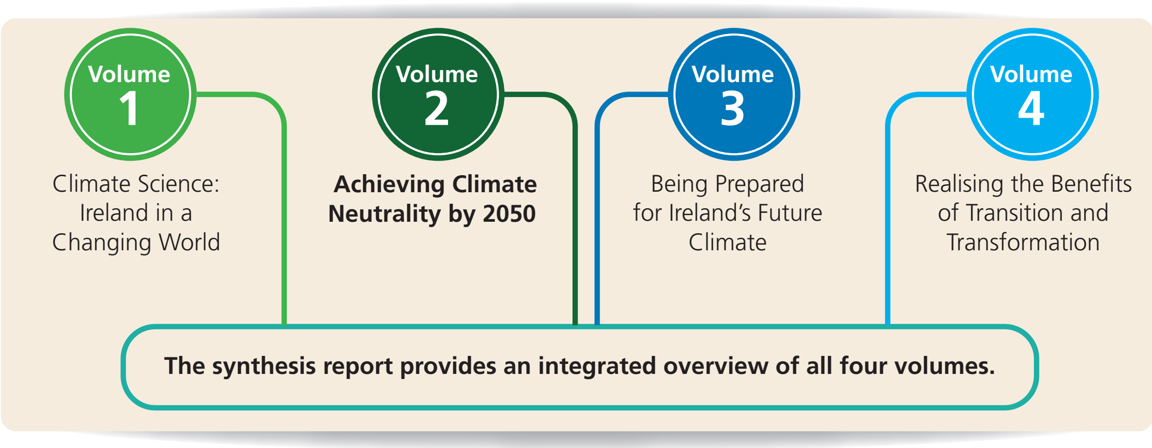
D.1	**Improving subnational analysis of greenhouse gas emissions and removals** Research is needed to improve subnational estimates of energy use and associated emissions, as well as emissions and removals from agriculture and land uses, and other emissions, potentially through the development of a distributed analysis system, dashboard or repository for sharing information. This should be linked with and support the official analysis provided by the national inventory system.
D.2	**Energy efficiency and demand-side management** Further research is required to understand the barriers to and drivers of energy efficiency and demand-side management in Ireland. This would help in understanding the enablers required for policymakers and stakeholders to develop targeted strategies to promote sustainable energy practices.
D.3	**Foresight into future technologies** More analysis is required to inform future energy choices beyond 2030 relating to the scale and magnitude of technologies that will help get us to net zero emissions.
D.4	**Quantifying carbon dioxide removals to bridge evidence gap** There is a need to quantify the extent of carbon dioxide removals required to provide a clear pathway for climate neutrality, which should take into account the climate impacts of emissions as well as the risks associated with the adoption of removal solutions, particularly nature-based solutions.
D.5	**Balancing agricultural emissions via management of terrestrial sinks** Despite the recognition of the importance of agricultural emissions and land use removals, there is a critical research gap in determining the specific levels of emissions that can feasibly be balanced with land use practice.
D.6	**Expanding use of observational data** Continued enhancement and development of the national inventory within the LULUCF sector is very important. This can be enabled by increasing use of observational data from soil flux towers and atmospheric sites, as well as the use of remote sensing and enhancing the activity data derived from such observations.
D.7	**Integrated assessments** Addressing the knowledge gaps is essential, including an integrated assessment of whole-of-economy transitions and transformation options. These would apply to agriculture, energy and land use.
D.8	**Mobilising climate action** Research is needed to identify effective strategies and interventions to effectively engage with citizens and communities, build societal capacity, and mobilise society-wide climate action.
D.9	**Integrating mitigation and adaptation** There is a critical need for research to uncover the synergistic co-benefits that can be derived from implementing integrated mitigation and adaptation measures.
D.10	**New economic paradigms: implications of transition to a low-carbon future** Addressing the research gap in Ireland regarding the economic implications of energy and livestock reductions is essential; this will provide policymakers and stakeholders with the insights necessary for evidence-based decision making and the development of targeted policies.

Table of contents

Preamble

The UN Framework Convention on Climate Change (UNFCCC, 1992) has the objective of preventing 'dangerous anthropogenic interference with the climate system', and the Paris Agreement (2015) established the long-term goals of 'holding the increase in 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' and of achieving 'a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'. Ireland's Climate Change Assessment (ICCA) delivers a comprehensive, Ireland-focused, state of scientific knowledge report on our understanding of climate change, its impacts on Ireland, the options to respond to the challenges it poses, and the opportunities from transitions and transformations to a climate-neutral, climate-resilient and sustainable economy and society. This serves to complement and localise the global assessments undertaken by the Intergovernmental Panel on Climate Change (IPCC) reports (see www.ipcc.ch). The findings presented build upon these global assessments and add important local and national context.

The report is presented in a series of four thematic volumes accompanied by an overarching synthesis report. The volumes are as follows:



Volume 2 Overview

This volume introduces our current best understanding of how to mitigate climate change with a central focus on Irish literature seeking to inform the pathway to a climate-neutral Ireland.

Chapter 1 introduces climate mitigation from a global context. It provides an explanation for key terms such as climate neutrality and net zero emissions, a summary of current global greenhouse gas emissions and an overview of the most recent IPCC assessment of global climate mitigation pathways. The purpose is to give the reader an understanding of the international landscape within which Ireland's climate action is taking place.

Chapter 2 focuses on Ireland's current greenhouse gas emissions and how policy in Ireland and the EU has increased ambition over the last few years and finishes by describing how our carbon budgets are considered. This chapter highlights emissions sources in Ireland and the different ways a carbon budget can be calculated, and it provides a summary of the carbon budget estimates for Ireland and an overview of the government agreed carbon budgets.

Chapter 3 provides an overview of Ireland's current energy system, looking at the decarbonisation challenge in terms of the fossil fuels we still rely on for the vast majority of our energy needs, and provides an overview on renewable energy targets and Ireland's energy security.

Chapter 4 delves into our future energy choices by technology. Beginning with the shorter term, technologies that are ready for market deployment, the chapter then moves into the wider range of other options available in the longer term, with an assessment of current stage of development and different uses in the Irish context and policy.

Chapter 5 provides further context to the technology options outlined in Chapter 4 by looking at the future energy choices by sector, in particular around travel and heat.

Chapter 6 focuses on the agriculture, forestry and land use changes specific to Ireland and related mitigation options from existing literature, focusing on Irish-based mitigation research.

Chapter 7 provides a synthesis of current studies on a net zero pathway for Ireland. While the available literature that this section draws on is limited, it is a critical element of this volume, pulling together the lessons from other chapters to look at how society-wide greenhouse gas emissions may be eliminated.

Chapter 8 introduces the societal dimension to the energy system and associated greenhouse gas emissions. This covers how behaviour shapes energy and emissions, the inequality within current energy and emissions policies, and a summary of the ways in which people can participate in the energy system transformation.

Chapter 9 closes with the key messages for closing the policy and research gaps identified throughout the assessment.

> *This volume introduces our current best understanding of how to mitigate climate change with a central focus on Irish literature seeking to inform the pathway to a climate-neutral Ireland.*

1

Understanding Global Climate Mitigation Pathways

Key messages

Climate change is undermining every dimension of global health monitored, increasing the fragility of the global systems that health depends on, and increasing the vulnerability of populations to the coexisting geopolitical, energy and cost-of-living crises.

The Paris Agreement signed by 198 countries in 2015 set goals to limit the increase in global temperatures to well below 2.0°C above pre-industrial levels, and to aim to curb the temperature increase to 1.5°C.

We are currently on the wrong path: global emissions increased by an average of 1.3% per year between 2010 and 2019.

We already have access to more fossil fuels than we can burn: the majority of fossil fuel reserves (60% of oil and gas, and 90% of coal) need to be left in the ground to stay below the 1.5°C carbon budget.

Remaining within the ‘safe’ temperature limits outlined in the Paris Agreement 2015 will require radical changes in energy and land use. Global greenhouse gas emissions need to be cut in half by 2030 and reach ‘net zero’ by mid-century.

There are no silver bullets: a wide range of mitigation measures are needed across all sectors, combining both demand-side reduction and supply-side improvements.

Many of the necessary technologies (e.g. wind, solar, bioenergy, electric vehicles, heat pumps) are already available for deployment at scale, but more are also needed (e.g. hydrogen, carbon capture, carbon dioxide removal).

While the current priority is to reduce emissions, in a net zero world we still have to deal with the existing/historical emissions. The removal of carbon dioxide from the atmosphere is deemed necessary to counterbalance the overshoot in emissions caused by hard-to-decarbonise sectors such as agriculture, heavy transport and industry.

The transition to a net zero future is not just technological: it requires transformations across society. While this statement may appear obvious, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is notable in that it is the first time that an IPCC assessment report features a specific chapter on the social aspects of emissions reduction.

Over the last century we have warmed our atmosphere, oceans and land in dangerous ways. The effects of these changes on the climate are already apparent, with many weather and climate extremes occurring across every region of the globe (Volume 1). For example, during the last decade, with an average temperature rise of 1.1°C above pre-industrial levels, extreme heat events occurred almost three times more frequently than in pre-industrial times (IEA, 2021b, p. 4). These changes will continue to impact Ireland's environment and society, which is also why adaptation is needed (Climate Change Advisory Council, 2022) (Volume 3).

While climate science is often complex to explain, the high-level solution is simple to communicate: to stop global warming, we must stop emitting greenhouse gas (GHG) emissions into the atmosphere (Volume 1). However, this simplicity betrays the remarkable practical challenges ahead in moving our society away from fossil fuels and destructive land and consumption practices.

The measures, costs and actions needed to avoid the most dangerous elements of climate change are well understood within the scientific community (both in Ireland and abroad). It will require rapid and far-reaching transformations in energy, land use, urban/rural living, infrastructure, industry, governance and finance systems. The necessary rate of change is unprecedented in terms of scale and, critically, speed. While there are historical examples of such rapid transformations associated with different sectors or technologies, these do not match the scale of the present challenge, which cross-cuts all aspects of society (IPCC, 2018a). It demands deep emission reductions in all sectors, a wide portfolio of climate mitigation options, significant upscaling of investments in clean technologies and a rethinking of businesses, governance and finance (Volume 4).

The transition to a climate-neutral society is both an urgent challenge and an opportunity to build a resilient future for all. All parts of society will play a role – from the power sector to industry, mobility, buildings, agriculture and forestry. This will require leadership from governance (policymakers, policy enforcers, etc.), business, communities and individuals. Combating climate change in the context of changing demography, cleaner and more affordable technologies, and increased digitalisation presents an opportunity to prepare for a safe, prosperous and competitive 21st century (Volume 4). The transformation away from a fossil fuel-based energy system is a vital part of the United Nations (UN) Sustainable Development Goals, and can be combined with a host of benefits such as improved human health and air quality, greater energy security, more efficient resource use and more economic and political stability in developing countries.

Climate science tells us that Earth systems will continue to change along the journey to net zero and that some changes will continue even after we have stopped emitting (Volume 1); thus, actions to reduce emissions will also need to go hand in hand with adaptation (Volume 3). The time to act is running out; decisions taken over the next decade (2020–2030) will be crucial (IPCC, 2022b).

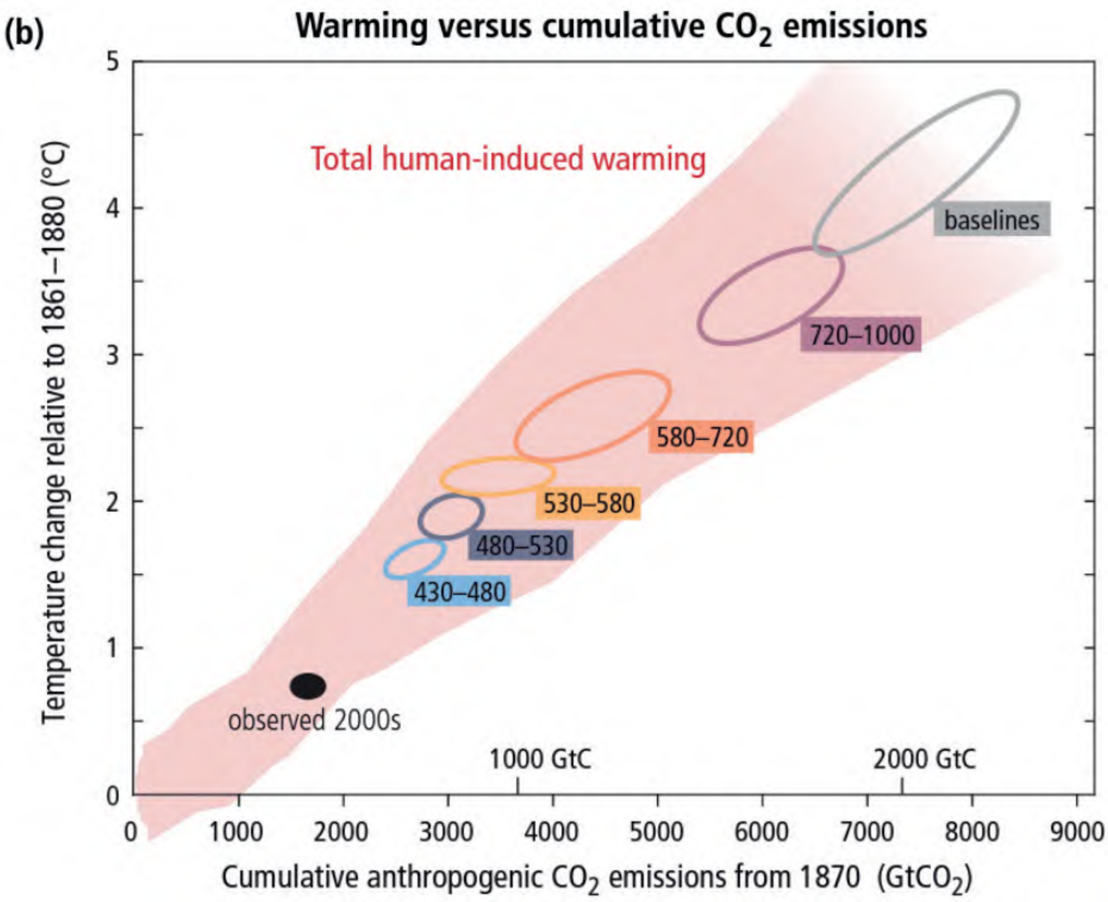
1.1 Achieving 'climate neutrality' and staying 'well below 2°C'

The Paris Agreement sets a clear global objective to limit human-induced climate change (section 1.1.2), built on well-established evidence that our emissions are causing the global temperature rise. However, despite three decades of global agreement and mounting scientific evidence, global GHG emissions are still on the rise (section 1.1.3).

1.1.1 The relationship between emissions and temperature

Box 1.1 Relationship between emissions and temperature: what does net zero or neutrality mean?

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C highlights the near-linear relationship between cumulative carbon emissions and global mean warming (IPCC, 2018a; Box 1.1, Figure 1). Therefore, limiting global warming implies a maximum amount of cumulative carbon dioxide (CO_2) emissions (carbon budget) and reaching a state when no further CO_2 emissions are added (net zero or neutrality).



Box 1.1 Figure 1 The relationship between global average temperature change and cumulative CO_2 emissions. Source: IPCC (2014; their figure SPM.5, panel b).

This means that halting the global average temperature rise at any level will require achieving net zero global CO_2 emissions at some point in the future. Furthermore, because of the cumulative carbon budget constraint, higher global emissions in the near term would require lower global emissions in the long term, and, in the event of overshooting (exceeding the budget), the use of CO_2 removal technologies.

Net zero CO_2 refers to the idea of balancing all sources of CO_2 emissions with means of removing them (often referred to as sinks) through the planet's natural absorption and other means (removal technologies).

However, achieving net zero CO_2 emissions is not sufficient to prevent further warming. Net zero CO_2 emissions would result in approximately stable CO_2-induced warming, but the overall level of warming will depend on any further warming contribution from other GHGs, such as methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (aerosols).

It is important to make the distinction between **climate neutrality**, which looks at all GHGs, and **carbon neutrality** (or **net zero CO_2**), which looks at CO_2 only. **Climate neutrality or GHG neutrality** is a state in which human activities result in no additional net effect on our climate system.

In the most recent Sixth Assessment Report (AR6), IPCC Working Group 3 (WGIII) did not use 'climate neutrality' and instead adopted GHG neutrality: "The term 'climate neutrality' is not used in this assessment because the concept of climate neutrality is diffuse, used differently by different communities, and not readily quantified" (IPCC, 2022b, p. 481). GHG neutrality is defined as a "Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions associated with a subject are balanced by metric-weighted anthropogenic GHG removals. The subject can be an entity such as a country, an organisation, a district or a commodity, or an activity such as a service and an event" (IPCC, 2022a, p. 1804). For the remainder of this volume, we understand climate neutrality to follow this definition of GHG neutrality.

Another important distinction with regard to emissions reporting is the difference between CO_2 and CO_2 equivalent values. Non-CO_2 emissions (CH_4 and N_2O) are generally expressed in terms of CO_2 equivalent values. These represent the global warming potential (GWP) of different gases (e.g. GWP_{100} is equivalent to the impact of CO_2 emissions over 100 years). This has implications for how net zero GHG emissions are defined. Calculating net zero GHG emissions with GWP_{100} would result in net cooling, while using GWP*, net zero GHG would result in no additional warming. The different metrics that can be used are covered in Volume 1, Chapter 2, and how it is currently handled with regard to Ireland's policy is outlined in section 2.4.3.

1.1.2 How climate policy has evolved

Since 1992, Ireland has been a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), and is thus committed to achieving the objective of this international treaty, as defined in Article 2: "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 1992, p. 4).

In 2015, Ireland was also a signatory to the Paris Agreement (UNFCCC, 2015). This landmark global agreement sets out our global climate mitigation goals (Box 1.2).

Box 1.2 Article 2 of the Paris Agreement

Article 2

1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

   (a) Holding 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, recognizing that this would significantly reduce the risks and impacts of climate change;

   (b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and

   (c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

2. This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

Source: United Nations Framework Convention on Climate Change (2015, p. 3).

The UNFCCC gives utmost importance to the stabilisation of GHG concentrations in the atmosphere. This requires that emissions of long-lived gases (CO_2) are reduced to net zero, and requires strong, rapid and sustained reductions in shorter-lived gases (CH_4). By setting temperature goals, the Paris Agreement sets a limit on emission levels, and, importantly, the pace at which they must reduce.

Article 4 of the Paris Agreement provides direction on how the temperature goal will be achieved (UNFCCC, 2015, pp. 6–8). It notes the need to:

1. reach a global peak in GHG emissions as soon as possible (recognising that peaking will take longer for developing economies);
2. undertake rapid reductions thereafter;
3. achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century.

Another core component of the Paris Agreement within Article 4 is what is often referred to as the 'ratchet mechanism'. Countries report their nationally determined contributions (NDCs) every 5 years in a global stocktake and then update their pledges accordingly. However, given the pressing need for emission reductions, developing countries have pushed for an annual review. The first global stocktake began at the UN Climate Change Conference in Glasgow in November 2021 (Conference of the Parties (COP) 26) and is due to conclude at COP28 in 2023 (UNFCCC, 2021).

1.1.3 Current global greenhouse gas emissions

The three key sources of emissions globally are CO_2 from burning fossil fuels, CH_4 from livestock, fossil fuel infrastructure and waste, and emissions associated with land use changes. The historical trend in GHG emissions from 1990 to 2019 is provided in Figure 1.1 and Table 1.1. Our global energy system based on fossil fuels is the single largest source at 64% of CO_2 equivalent (CO_2-eq) in 2019.

Table 1.1 *Global net anthropogenic greenhouse gas emissions and uncertainties by gas in 2019 relative to 1990*

GHG	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	1990–2019 increase (%)
CO_2-FFI	38 ± 3	15	167
CO_2-LULUCF	6.6 ± 4.6	1.6	133
CH_4	11 ± 3.2	2.4	129
N_2O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	**59 ± 6.6**	**21**	**154**

CO_2-FFI, CO_2 from fossil fuel combustion and industrial processes; CO_2-LULUCF, net CO_2 from land use, land use change and forestry; F-gases, fluorinated gases (hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride). Source: IPCC (2022b; their figure SPM.1).

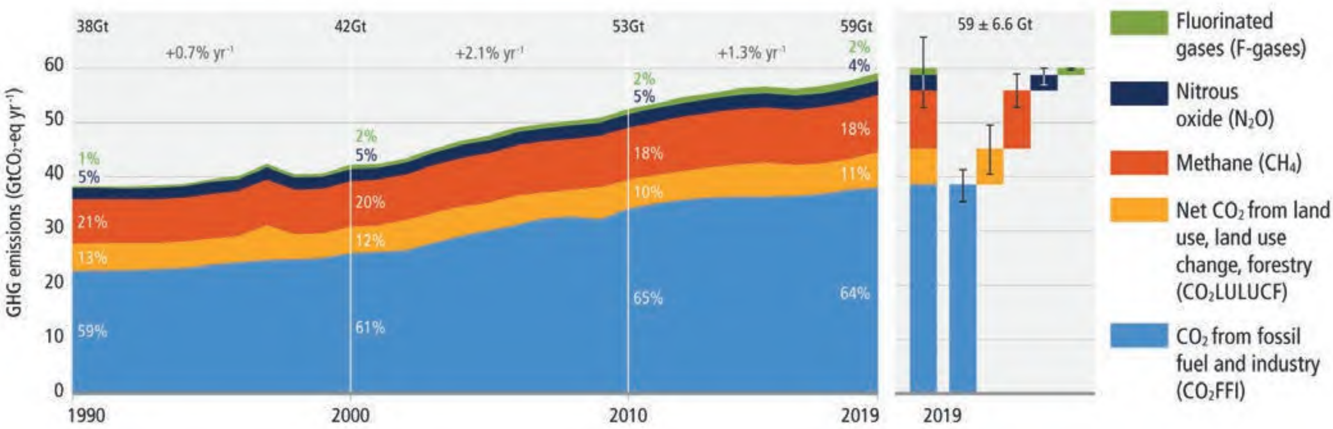


Figure 1.1 Global net anthropogenic greenhouse gas emissions ($GtCO_2$-eqyr^{-1}) 1990–2019. Source: IPCC (2022b; their figure SPM.1).

Attributing GHG emissions to the different sectors of society is a useful way to see where our GHG emissions come from (Figure 1.2). This more clearly points us to the drivers of GHG emissions, such as transport, agriculture or industry. Our lives are inextricably linked to energy and GHG emissions by what we eat, where we live, the ways we move around, the goods and services we produce and how we stay warm or cool.

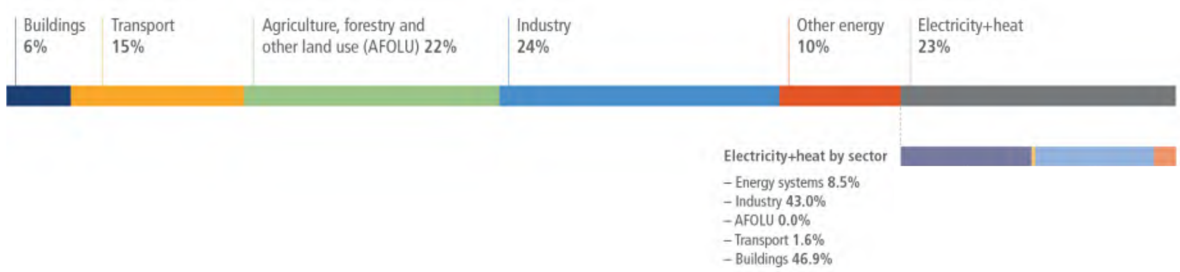


Figure 1.2 Total anthropogenic direct greenhouse gas emissions (59 $GtCO_2$-eq) for the year 2019. Source: IPCC (2022b; their figure TS.6, top panel).

Despite long-standing global agreement on the need to reduce emissions (section 1.1.2), they are still on the rise. Between 2010 and 2019, GHG emissions increased across all major sectors globally (IPCC, 2022b). Almost half (42%) of historical cumulative net CO_2 emissions since 1850 occurred between 1990 and 2019 (1,000 ± 90GtCO_2), and around 17% occurred between 2010 and 2019 (410 ± 30GtCO_2). Cumulative net CO_2 emissions over the last decade (2010–2019) were about the same size as the remaining carbon budget to limit warming to 1.5°C (IPCC, 2022b).

1.2 Global climate mitigation scenarios and pathways

Scientists use computer models to explore future scenarios of the world and its climate. These models are not perfect, given the highly complex system they try to represent and its unpredictability, but have been shown to simulate recent warming and globally warm climates of the geological past to a high degree of accuracy (as outlined in Cross-volume Box 1, Volume 1). Modelled scenarios are also often referred to as pathways. These pathways illustrate what reduction in emissions and actions are needed to deliver a certain global temperature. Scenarios developed with models of the combined energy–economy–environment system provide key tools to explore how the future could evolve and how today's decisions affect longer-term outcomes.

1.2.1 What are scenarios and pathways?

IPCC publications use illustrative scenarios that cover the range of possible future development of anthropogenic drivers of climate change found in the literature (Volume 1). These scenarios explore how the future may develop based on a coherent and internally consistent set of assumptions about key drivers, including demography, economic processes, technological innovation, governance and lifestyles, and relationships between these driving forces. They are useful for understanding the long-term implications of and responses to short- to medium-term decisions and trends. It is important to note that these are not predictions of the future but rather computer-based simulations of potential emission pathways. Another key thing to note is that the output of the models will in large part be defined by the input assumptions and model structure.

The scenarios represent possible sets of decisions by humanity, without any assessment that one set of decisions is more likely to be made than any other set. Scenario storylines attempt to "stimulate, provoke, and communicate visions of what the future could hold for us" (Rounsevell and Metzger, 2010, p. 606) in settings where either limited knowledge or inherent unpredictability in social systems prevent a forecast or numerical prediction. A range of different possible scenarios are developed to try to cover the variety of potential outcomes. As outlined in McMullin and Price (2020a, p. 4), "scenario planning is essential for exploring the very wide range of possible futures. By developing a limited number of challenging but plausible scenario narratives, the risks of catastrophic outcomes can be properly identified, managed and, ideally, completely avoided. Scenario development should reflect society-wide values and goals."

There are many paths to achieving climate neutrality by 2050. For example, the IPCC Special Report on 1.5°C reviewed 78 different global pathways to meet this ambition (Huppmann et al., 2018). In the most recent assessment from the IPCC, seven pathways were developed from a collection of 1,202 scenarios from a wide range of modelling approaches (IPCC, 2022b). These pathways condense this very large set of scenarios into a representative range of different mitigation strategies that would be consistent with different warming levels (outlined in section 1.2.3).

Focusing on end-of-century outcomes, combined with discounting long-term compared with present-day mitigation, leads to a feature that is present in virtually all resulting scenarios: the assumed possibility of substantial net negative CO_2 emissions in the second half of the century allows for weaker reductions in emissions in the nearer term and results in temporarily higher warming levels over the course of the century .

A key variable that has raised questions is the discount rate, as it has serious consequences for inter-generational equity (Dasgupta, 2008; Emmerling et al., 2019). The discount rate is a commonly used economic principle that assumes that people in the future will be better able to pay. It makes current costs appear more substantial than future investments: "The discount rate has a significant impact on the balance between near-term and long-term mitigation. Lower discount rates <4% (than used in IAMs) may lead to more near-term emissions reductions" (IPCC, 2022b, p. 454). This is a long-documented limitation of current approaches (Ackerman et al., 2009). It has long been argued that the discount rate should be zero or even negative when it comes to assessing climate change policies, as the long-term benefits far outweigh the costs, and future populations may in fact be less able to pay due to the current inaction (Fleurbaey and Zuber, 2012; Portney and Weyant, 2013). Emmerling et al. (2019) highlight that reducing the discount rate in integrated assessment models (IAMs) from 5% to 2% would result in a significant reduction in the carbon budget overshoot and thus the scale of net negative emissions required over this century.

Another key omission is that the models do not account for the cost of climate change, negative impacts of fossil fuels and co-benefits of mitigation. As noted in the IPCC's Special Report on Global Warming of 1.5°C (SR1.5): "limitations remain, as climate damages, avoided impacts, or societal co-benefits of the modelled transformations remain largely unaccounted for" (Rogelj et al., 2018, p. 95). This means that mitigation measures are assessed based only on investment costs, while the potential climate impacts on economic activity are omitted: "none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth" (Rogelj et al., 2018, p. 109). In the more recent AR6, the economic argument for climate mitigation is clear: "Models that incorporate the economic damages from climate change find that the global cost of limiting warming to 2°C over the 21st century is lower than the global economic benefits of reducing warming" (IPCC, 2022b, p. 496).

1.2.2 The difference between 1.5°C and 2°C

Achieving the Paris Agreement will require global emissions of all GHGs to reduce rapidly over the next few decades, with more rapid decreases needed to limit warming to 1.5°C. The models show that limiting global warming to 1.5°C requires unprecedented changes across society, energy and land use. This radical transformation of how we live will require a cross-society effort. The necessary emission reductions for the coming decades were summarised by the IPCC as follows:

In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070. (IPCC, 2018b, p. 12)

The enormity of this challenge is striking when you consider that between 2010 and 2019 global GHG emissions increased at an average rate of 1.3% per year (Figure 1.1). Delayed climate action to date now means that GHG emission reductions must be achieved very rapidly (Figure 1.3).

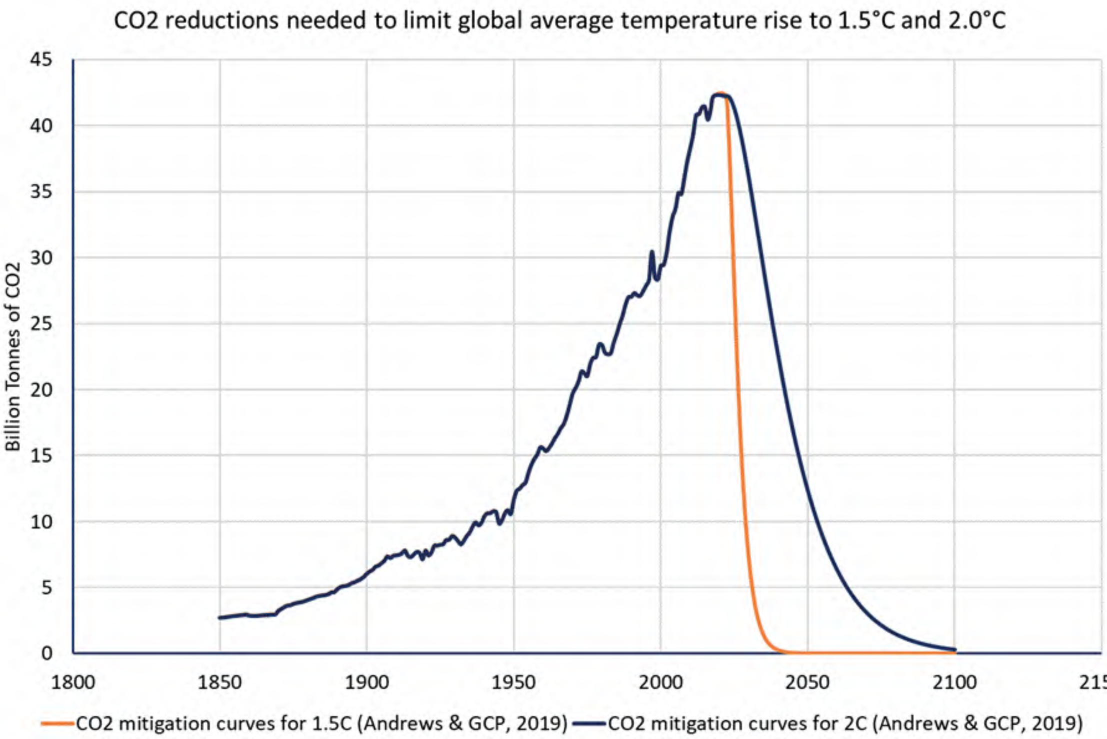


Figure 1.3 Global emissions reduction scenarios necessary to limit global average warming to 1.5°C and 2.0°C, starting from 2022 with a 66% chance of success. These 'mitigation curves' are based on the carbon budget outlined in the IPCC's Special Report on 1.5°C (IPCC, 2018a) and the methodology for converting a cumulative carbon budget into annual quotas from Raupach et al. (2014). They are based on the assumption of zero negative emissions (actively removing CO_2 from the atmosphere). The extent of our reliance on removal technologies will be determined by how quickly decarbonisation in all sectors occurs. Source: alphacast (2023). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/)

In 2019, global energy-related CO_2 emissions were around 38GtCO_2 (Table 1.1). For a 50% chance of limiting the temperature rise to 1.5°C, the IPCC Special Report estimated that at the end of 2017 the remaining carbon budget was between 580 and 770GtCO_2 (IPCC, 2018a). These different budgets reflect different approaches to determining the extent to which warming has already taken place, uncertainties in the climate response to CO_2 and non-CO_2 gases, and the level of future releases from permafrost thawing and wetlands. The level of non-CO_2 (primarily CH_4) mitigation, which has a strong short-term effect on the temperature rise (Volume 1), could alter the remaining carbon budget by 250GtCO_2 in either direction (IPCC, 2018a).

The difference between a temperature rise of 1.5°C and 2°C has serious consequences for global ecosystems and our wellbeing (Volumes 1 and 3). The higher the temperature rise, the greater the risks of severe weather events such as extreme heat, drought, river and coastal flooding and crop failures (IPCC, 2018a). The extent of these impacts will be determined by the effort made across society to limit our emissions. It is dependent on how much we continue to emit before reaching the point of net zero emissions.

1.2.3 Paris-aligned pathways to avoid the worst elements of climate change

1.2.3.1 Where are we now?

Modelling by the International Energy Agency (IEA) showed that stated government global policies as of 2019 fell short of net zero and would result in a 2.1°C temperature increase by 2100 (IEA, 2021a). More recent analysis, assessing the pledges (NDCs) submitted prior to COP26 in November 2021, has highlighted that there is still a significant gap between existing efforts and the necessary reductions to achieve the Paris Agreement temperature goals (Figure 1.4). The gap between Paris Agreement pathways and projected global emissions in 2030 based on policies implemented by the end of 2020 and NDCs announced prior to COP26 is quite significant, at 6–16GtCO_2-eqyr^{-1} for 2°C, and 16–26GtCO_2-eqyr^{-1} for 1.5°C with no or limited overshoot (IPCC, 2022b).

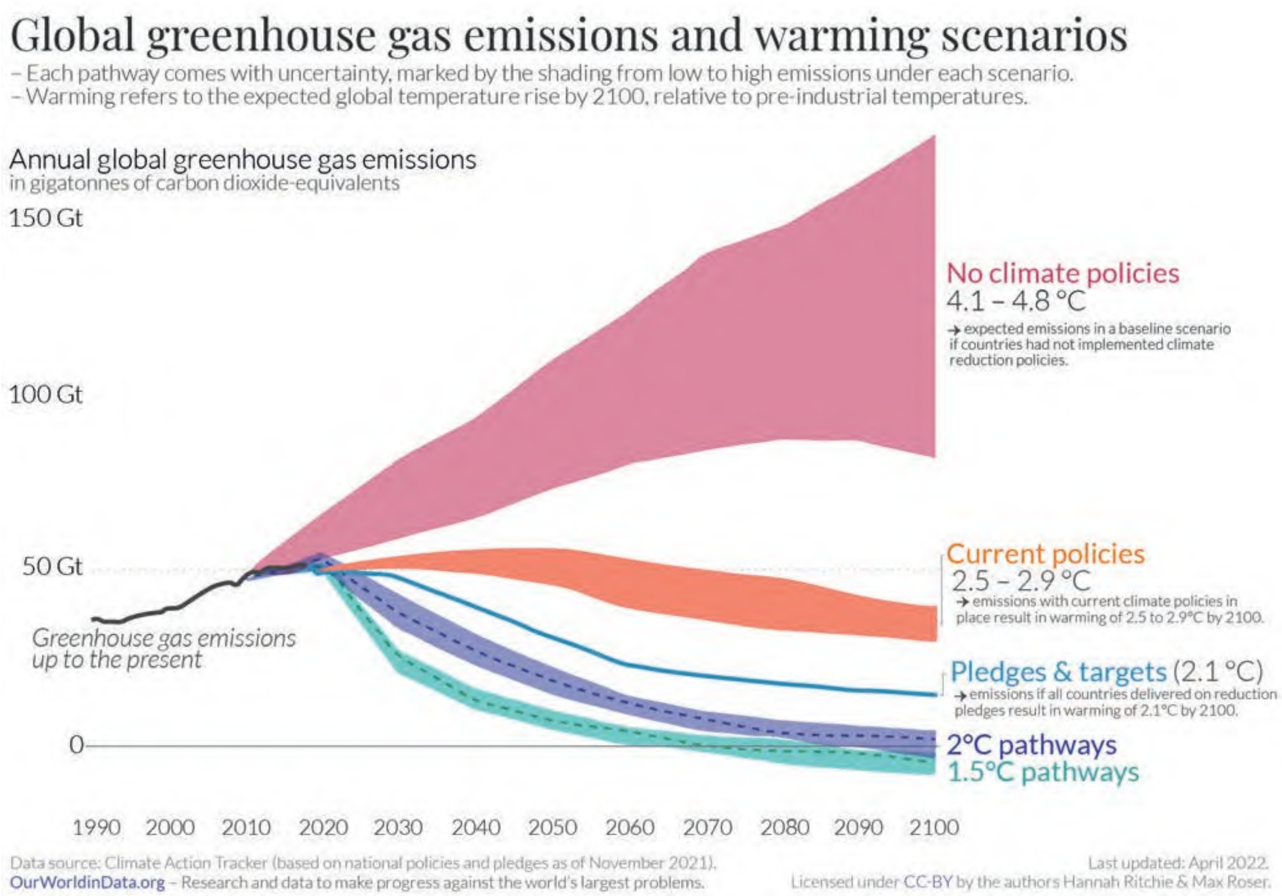


Figure 1.4 Global greenhouse gas emissions and associated warming under current government policy and pledges, April 2022. Source: Prepared by Ritchie et al. (2022), based on data from Climate Action Tracker (2021). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

At the end of 2022, several reviews raised serious concerns that global emissions and current climate policies are not on the right path (Boehm et al., 2022; Fransen et al., 2022; UNEP, 2022; UNFCCC, 2022). The UNEP Emissions Gap Report 2022 highlighted a significant gap between current efforts and the Paris Agreement temperature goals (UNEP, 2022). It estimates that the unconditional NDCs give a 66% chance of limiting global warming to about 2.6°C by the end of the century, while conditional NDCs bring this down to 2.4°C. Based on policies currently in place, without further strengthening, a 2.8°C rise is suggested. Similarly, the synthesis report based on the 166 NDCs that are available from the 193 parties to the Paris Agreement noted worrying trends (UNFCCC, 2022):

- The total global GHG emission level in 2030, taking into account implementation of all the latest NDCs, is expected to be 15.9% above 2010. According to the SR1.5, to be consistent with global emission pathways with no or limited overshoot of the 1.5°C goal, global net anthropogenic CO_2 emissions need to decline by about 45% from the 2010 level by 2030, reaching net zero around 2050. To limit global warming to below 2°C, CO_2 emissions need to decrease by about 25% from the 2010 level by 2030 and reach net zero around 2070.
- Looking at the carbon budget, cumulative CO_2 emissions in 2020–2030 based on the latest NDCs would probably use up 89% of the remaining carbon budget, consistent with a 50% likelihood of limiting warming to 1.5°C, leaving a post-2030 carbon budget of around 56GtCO_2, which is equivalent to the average annual CO_2 emissions estimated for 2020–2030.

The 2022 report of the Lancet Countdown on health and climate change echoed much of these concerns (Romanello et al., 2022), also stressing that climate change is undermining every dimension of global health monitored, increasing the fragility of the global systems that health depends on, and increasing the vulnerability of populations to the coexisting geopolitical, energy and cost-of-living crises.

1.2.3.2 What needs to change?

The science shows that there are several pathways to limit the global temperature increase to 1.5°C (Rogelj et al., 2018). These pathways differ in terms of technology deployment but can be understood to have some key features: (1) significant reduction in fossil fuel use, (2) the important role of increasing energy efficiency and reducing energy demand, (3) massive deployment of renewable energy and (4) the potential role of carbon capture, storage and removal. While there are different options for exactly how we can achieve the temperature goal, one thing is clear: we are currently on the wrong path (section 1.2.3.1). Current policies are not sufficient to meet the Paris temperature goals, and we already have access to more fossil fuels than we can burn. Welsby et al. (2021) found that nearly 60% of oil and fossil methane gas, and 90% of coal, must remain unextracted to keep within a 1.5°C carbon budget. The IPCC WGIII AR6 warned that existing fossil fuel infrastructure has already committed us to exceeding the 1.5°C target:

> *Projected cumulative future CO_2 emissions over the lifetime of existing and currently planned fossil fuel infrastructure without additional abatement exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C with no or limited overshoot. They are approximately equal to total cumulative net CO_2 emissions in pathways that limit warming to 2°C. (IPCC, 2022c, p. 20)*

As introduced in section 1.2.1, the most recent IPCC assessment developed seven representative pathways (Table 1.2 and Figure 1.5). These are split into two sets: two reference pathways illustrative of high emissions and five illustrative mitigation pathways (IMPs). The IMPs explore different levels of mitigation ambition and, critically, the level of reliance on carbon dioxide removal (CDR). The purpose of the IMPs is to illustrate a set of important themes.

> *There is still a significant gap between existing efforts and the necessary reductions to achieve the Paris Agreement temperature goals (Figure 1.4)*

Table 1.2 *IPCC WGIII AR6 seven selected scenarios and associated temperatures (with climate emulator in brackets)*

Temperature rise	Scenario	Description
Below 4°C (C7)	Current policies (CurPol)	Implementation of current climate policies (mostly as reported in NDCs), neglecting stated subsequent goals and objectives (e.g. for 2030); only gradual strengthening after 2030
Below 3°C (C6)	Moderate action (ModAct)	Implementation of current policies and achievement of 2030 NDCs, with further strengthening post 2030. Similarly to the situation implied by the diversity of NDCs (both policies and pledge), a fragmented policy landscape remains
Likely to be below 2°C (C3)	Gradual strengthening of current policies (GS)	Until 2030, primarily current NDCs are implemented; after that a strong, universal regime leads to coordinated and rapid decarbonisation action
Below 1.5°C with high overshoot (C2)	Extensive use of net negative emissions (Neg)	Successful international climate policy regime reduces emissions below ModAct or GS to 2030, but with a focus on the long-term temperature goal; negative emissions kick in at growing scales thereafter, so that mitigation in all sectors also includes a growing and ultimately large reliance on negative emissions, with large 'net global negative' after 2050 to meet 1.5°C after significant overshoot
Below 1.5°C with no or limited overshoot (C1)	Renewables (Ren)	Successful international climate policy regime with immediate action, particularly policies and incentives (including international finance) favouring renewable energy; less emphasis on negative-emission technologies. Rapid deployment and innovation of renewables and systems; electrification of all end use
	Low demand (LD)	Successful international climate policy regime with immediate action on the demand side; policies and financial incentives favouring reduced demand that in turn leads to early emission reductions; this reduces the decarbonisation effort on the supply side
	Shifting pathways (SP)	Successful international climate policy regime with a focus on additional SDG policies aiming at, for example, poverty reduction and broader environmental protection. Major transformations shift development towards sustainability and reduced inequality, including deep GHG emission reductions

Source: Compiled by the authors from data in IPCC (2022b).

Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.

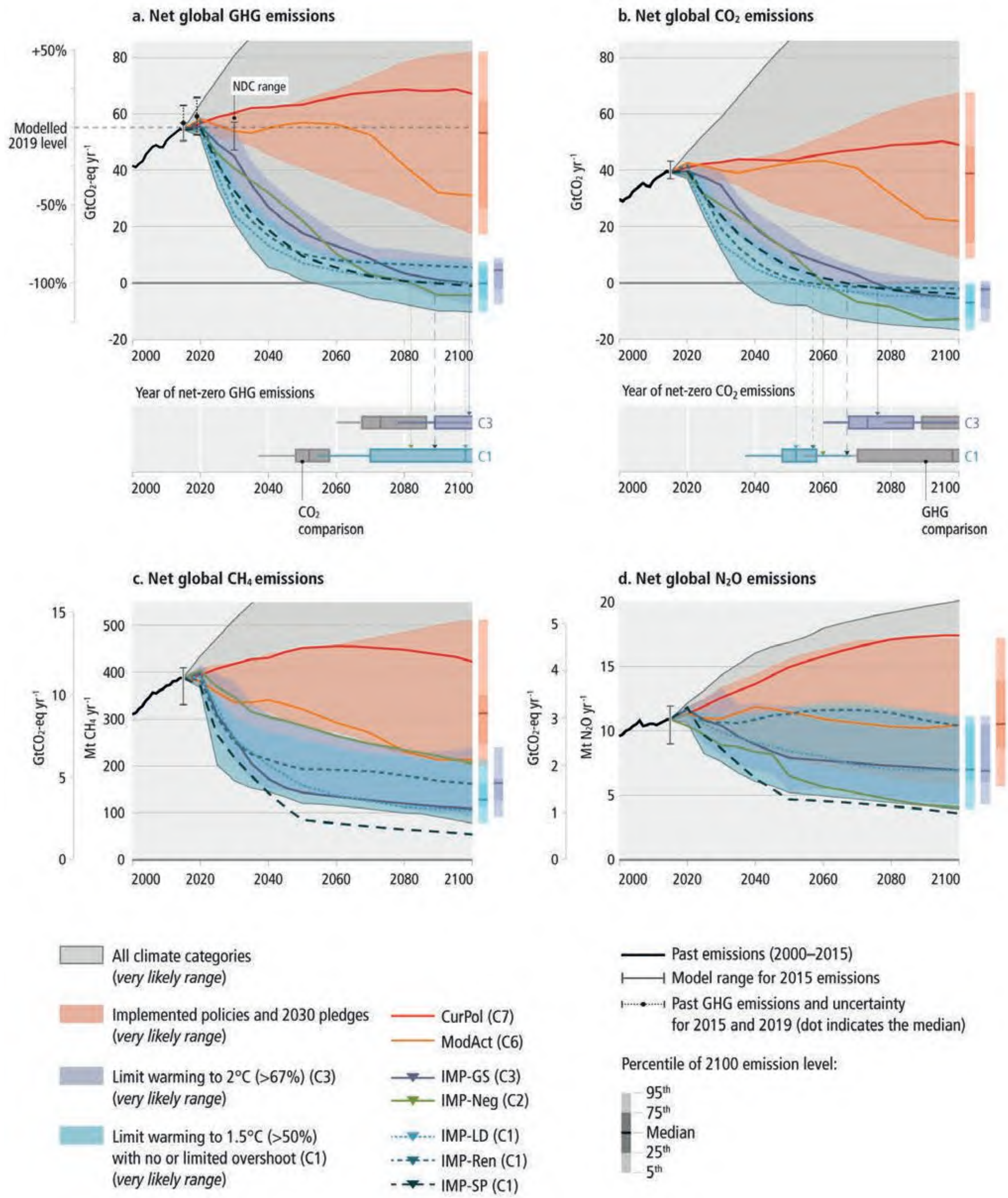


Figure 1.5 Overview of the net (a) greenhouse gas, (b) CO_2, (c) CH_4 and (d) N_2O emissions for each illustrative mitigation pathway. Source: IPCC (2022b; their figure SPM.5).

Box 1.3 Key messages on mitigation pathways from IPCC WGIII AR6

The timing of global net zero emissions:
"For the scenarios in the C_1 category (warming below 1.5°C (50% probability) with limited overshoot), the net zero year for CO_2 emissions is typically around 2035–2070. For scenarios in C_3 (likely limiting warming to below 2°C), CO_2 emissions reach net zero around 2060–2100. The GHG net zero emissions year is typically around 10–20 years later than the carbon neutrality" (IPCC, 2022b, p. 324).

Some emissions will not get to zero:
"In pathways limiting warming to 2°C (>67%), methane is reduced by around 19% (3–46%) in 2030 and 46% (29–64%) in 2050, and in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot by around 34% (21–57%) in 2030 and a similar 51% (35–70%) in 2050" (IPCC, 2022b, p. 324).

After reaching net zero, CO_2 will need to go negative to balance other emissions:
"some CH_4, N_2O and F-gas emissions from, for example, agriculture and industry, will remain over the course of this century. Net negative CO_2 emissions will therefore be needed to balance these remaining non-CO_2 GHG emissions to obtain net zero GHG emissions" (IPCC, 2022b, p. 328).

Later action (GS) leads to heavier reliance on removals:
"delays in mitigations actions are compensated by net negative emissions in the second half of the century" (IPCC, 2022b, p. 341). While strong reductions in demand (LD and SP) can reduce reliance on bioenergy and CDR, "There is a clear distinction between the scenarios with no or limited overshoot (typically <0.1°C, C_1) compared to those with high overshoot (C_2): in emissions, the C_1 category is characterised by steep early reductions and a relatively small contribution of net negative emissions" (IPCC, 2022b, p. 318).

The sooner we act, the lower the long-term cost:
"Modelled pathways with a peak in global emissions between now and 2025 at the latest, compared to modelled pathways with a later peak in global emissions, entail more rapid near-term transitions and higher up-front investments, but bring long-term gains for the economy" (IPCC, 2022b, p. 37).

There can be no new fossil fuel infrastructure:
"the Paris climate goals could move out of reach unless there are dedicated efforts for early decommissioning, and reduced utilisation of existing fossil fuel infrastructures, cancellation of plans for new fossil fuel infrastructure or compensation efforts by removing some of the CO_2 emissions from the atmosphere" (IPCC, 2022b, p. 267).

Electricity will play a central role in the future energy system:
"Stringent emissions reductions at the level required to limit warming to 2°C or 1.5°C are achieved through increased electrification of end-use, resulting in increased electricity generation in all pathways" (IPCC, 2022b, p. 496).

100% renewable energy studies are not included in the IPCC assessment:
There has been much debate in the literature on the possibility of 100% renewable energy systems (Heard et al., 2017; Brown et al., 2018). Having previously been dismissed as technically unfeasible, the potential for 100% renewable energy systems has recently been gaining a lot of traction (Hansen et al., 2019; Breyer et al., 2022). However, the fact these are limited to energy system models that do not cover non-energy GHGs

means they are excluded from the IPCC scenarios: "Scenarios have been published with 100% renewable energy systems even at a global scale, partly reflecting the rapid progress made for these technologies in the last decade (Breyer and Jefferson, 2020); (Creutzig et al., 2017); (Jacobson et al., 2018). These scenarios do not show in the graph due to a lack of information from non-energy sources" (IPCC, 2022b, p. 332). The pathways thus have a high reliance on carbon capture and storage.

Reductions in demand make mitigation easier:
"Demand-side mitigation and new ways of providing services can help Avoid and Shift final service demands and Improve service delivery. Rapid and deep changes in demand make it easier for every sector to reduce GHG emissions" (IPCC, 2022b, p. 505).

Rapid reductions in methane may provide negative emissions:
"Using GWP* as a metric results in a significant change, not only in the timing of net zero emissions, but also the overall shape of the CO_2-eq emissions pathway … The reason for those different shapes of CO_2-equivalent emission trajectories under GWP* is that this metric translates rapid reductions of CH_4 emissions into negative CO_2-equivalent emissions" (IPCC, 2022b, p. 2SM–28).

This is a societal problem, not just an engineering challenge:
Importantly, the IPCC (2022b) highlights that the transition to net zero energy systems is not just technological; it requires shifts in institutions, organisations and society more generally. While this statement may appear obvious, this Sixth Assessment Report of the IPCC is notable in that it is the first time that an IPCC assessment report features a specific chapter (Chapter 5) on the social aspects of emission reduction.

1.2.4 The role of carbon capture and storage, and removal

1.2.4.1 Carbon capture, utilisation and storage

Carbon capture and storage (CCS) could allow the continuation of conventional fossil fuel power plants or industrial processes (such as steel and cement production) but the emissions would be captured and then stored in geological reservoirs (i.e. empty oil or gas fields). Alternatively, the captured carbon could be converted into synthetic fuel or other feedstocks needed in industry, a process known as carbon capture and utilisation (CCU) (Al-Mamoori et al., 2017; Baena-Moreno et al., 2019; IEA, 2021a). It is important to note that the availability of data and information regarding the adoption of CCS/CCU at scale remains unclear. Despite its prominence in IPCC scenarios, the deployment rate has been slow: "Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C" (IPCC, 2022b, p. 28).

CCS in power generation is generally deemed necessary to provide a flexible source of electricity that can ensure balance in a system with high shares of variable renewables (Mikulčić et al., 2019). The IPCC pathways do not consider 100% renewable energy studies, and thus: "In the majority of the scenarios reaching low greenhouse targets, a considerable amount of CCS is applied" (IPCC, 2022b, p. 332). In addition, in heavy industry such as cement and steel production, CCS is currently the only solution that can provide deep emission reductions.

A report by the Institute for Energy Economics and Financial Analysis reviewed 13 flagship cases (10 in operation, two that have failed and one that has been suspended) equating to around 55% of the total nominal capture capacity operating worldwide (Robertson and Mousavian, 2022). The key message was that failed or underperforming projects considerably outnumbered successful experiences. Bui et al. (2018), in their review of ways forward for the technology, showed that most applications are in the technology readiness level (TRL) 3 (proof of concept), TRL 6 (pilot) and TRL 7 (demonstration) phases. For those at the TRL 3 stage more research funding is required, while moving those at TRL 6 and TRL 7 to commercially viable developments is dependent on financial capital investment and/or commercial interest.

The two key barriers at present are the limited policy support in most countries and significant financial uncertainties (Bui et al., 2018; Durmaz, 2018). A previous review from 2015 showed that, despite the prominence of such technologies in global mitigation pathways, NDCs prepared by countries included very limited deployment of CCS (Spencer et al., 2015). Bui et al. (2018) identify five commercial risks that they suggest should be covered by public financing/support to reduce the risk faced by private investment:

1. cross-chain default – lack of transport and storage technologies limit capture viability;
2. post-decommissioning CO_2 storage risk;
3. CO_2 storage performance risks;
4. decommissioning cost and financial securities related to the CO_2 storage permit;
5. insurance market limitations for CO_2 transport and storage operations.

1.2.4.2 Carbon dioxide removal

CDR from the atmosphere is likely to be needed to keep the global temperature rise 'well below' 2°C, and to be necessary in achieving the more difficult 1.5°C target (Rogelj et al., 2018). All pathways in the IPCC Special Report on 1.5°C contain CDR, "but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land-use (AFOLU) sectors" (IPCC, 2018b, p. 14). Similarly, in the more recent AR6, all the IMPs (section 1.2.3) contained CDR in the form of natural sinks (primarily afforestation/reforestation) and/or bioenergy with carbon capture and storage, with some also including direct air capture (IPCC, 2022b). This is because for some sources of CO_2 (e.g. heavy industry) and non-CO_2 emissions (e.g. livestock), options for mitigating them have not yet been identified. Even when other sectors reach zero emissions, this leads to cumulative emissions of GHGs being greater than levels that are compatible with avoiding dangerous climate change, which is often referred to as 'overshoot'. In addition, while the current focus is on reducing emissions, in a net zero world we will still have to deal with existing/historical emissions (King et al., 2022). Figure 1.6 highlights the anthropogenic interactions between the carbon sources and sinks.

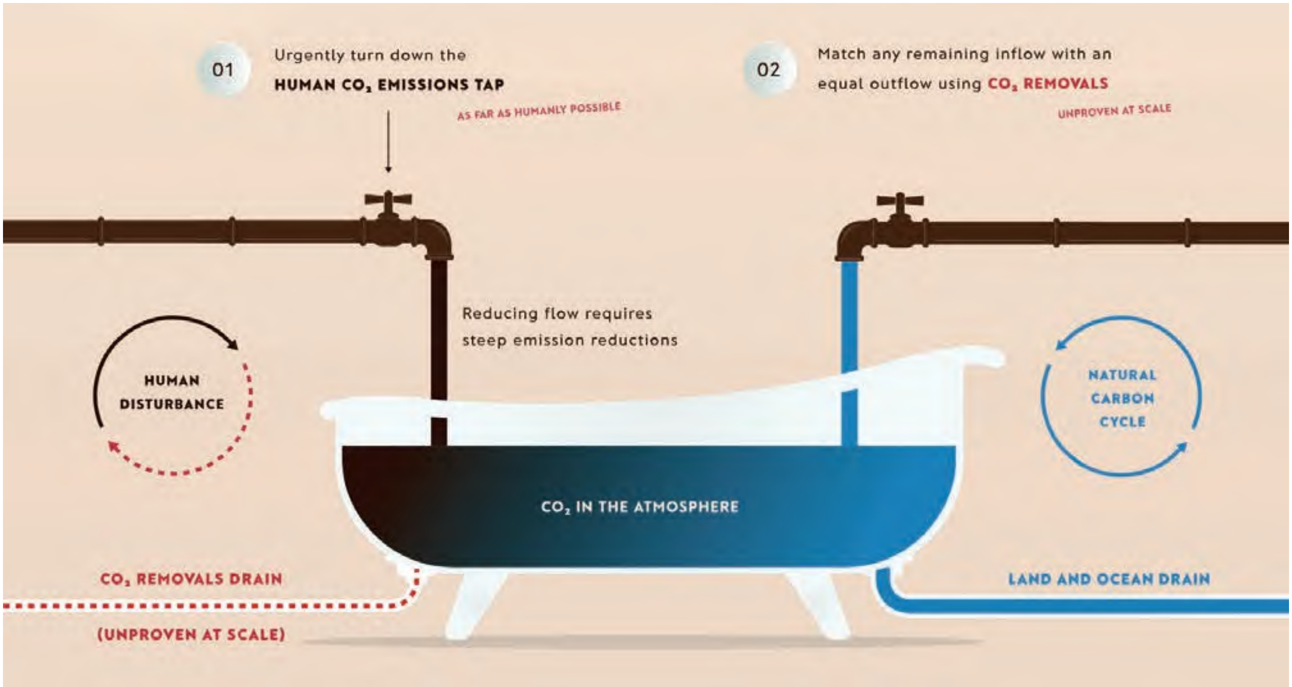


Figure 1.6 Illustration of carbon sources and sinks. Source: Lang (2022). Reproduction licensed under the Creative Commons Attribution CC BY-ND 4.0 licence (https://creativecommons.org/licenses/by-nd/4.0/).

There are three prominent examples of negative emissions:

- Natural sinks/carbon sequestration, where vegetation and soils naturally absorb carbon. These 'nature-based solutions' offer a useful means of carbon storage and, if managed correctly, can have important co-benefits for biodiversity (Di Sacco et al., 2021).
- Bioenergy with carbon capture and storage (BECCS), which involves growing biomass (i.e. forestry or other woody crops) that can then be burned in a power plant with CCS (section 1.2.4.1).
- Direct air carbon capture and storage (DACCS), which involves mechanically sucking CO_2 out of the atmosphere.

In the IPCC pathways, the success of climate mitigation in the first half of this century determines the extent of our reliance on CDR, which may have serious implications for land use: "IAM pathways rely on afforestation and BECCS as CDR measures, so delayed mitigation action results in substantial land-use change in the second half of the century with implications for sustainable development (Hasegawa et al., 2021)" (IPCC, 2022b, p. 347). Afforestation and land use change are seen as critical means to restore natural carbon sinks (Roe et al., 2019). Further to this, the negative emissions provided by BECCS are crucial in balancing hard-to-mitigate areas. However, the increasing competition for land between energy crops, carbon sequestration and food needs to be carefully managed (Calvin et al., 2014; Fujimori et al., 2019; Doelman et al., 2020). While the large-scale growth of monoculture bioenergy crops may be good for climate mitigation, it can have negative impacts on other sustainability criteria (Calvin et al., 2021).

Various literature studies (e.g. Beuttler et al. (2019), Realmonte et al. (2019)) have estimated the CO_2 removal potential of a range of technologies on a global scale with different degrees of certainty, but national assessments that consider local details and impacts across the wider energy system are less common. Two key limiting factors of DACCS is the rate at which it can be scaled up and the amount of energy it may require. There is a serious risk of global temperature overshoot if it is not available at scale (gigatonnes CO_2) before 2050 (Beuttler et al., 2019). Furthermore, questions have been raised about how much of global energy demand it may account for (Realmonte et al., 2019).

1.2.5 The role of demand-side measures

There is growing interest in alternative scenarios that reduce the need for CDR by changing patterns of consumption and reducing energy demand (Creutzig et al., 2018; Grubler et al., 2018; Van Vuuren et al., 2018). Some have highlighted that the dependence on CDR stems from the underlying model assumption of continued growth in material and resource consumption (Hickel et al., 2021; Lenzen et al., 2022).

Pye et al. (2021) highlight that the traditional supply-side focus of many energy system models, and lack of demand-side options included, leads to an overreliance on CDR options. They call for new approaches to develop net zero energy system pathways. There is a growing number of studies proposing lower energy demand, which importantly does not reduce quality of life. The Centre for Research into Energy Demand Solutions (CREDS) assessment of energy demand reduction as a way of achieving net zero in the UK highlights that achieving net zero emissions by 2050 without substantial reductions in energy demand will be extremely difficult and more expensive than other options (Barrett et al., 2021). This calls for a rethinking of our lifestyles (consumption habits in terms of goods and services) as well as more strategic spatial planning to deliver compact development with lower transport and heating demand.

For non-energy emissions, in particular agriculture, there are limited options available for supply-side mitigation in terms of both the production efficiencies currently available and potential future options in research and development (Wollenberg et al., 2016; Kuramochi et al., 2018). This results in a need for the energy system to provide negative emissions in order to compensate for the fact that agriculture cannot get to net zero.

Since our present agricultural system comes with such a significant social and climate cost (Errickson et al., 2021), a switch from animal- to plant-sourced protein offers substantial potential for GHG emission reductions (Harwatt, 2019; IPCC, 2022b). The EAT-Lancet Commission proposes a 'Planetary Health Diet', with reduced meat consumption, to benefit both people and the planet (Willett et al., 2019). From a review of the health and environmental implications of adopting national food-based dietary guidelines in 85 countries, Springmann et al. (2020) found that 0ne-third (29; 34%) were incompatible with the Paris Agreement on climate change. They demonstrate that adopting the EAT-Lancet recommendation would not only significantly reduce emissions but also have other important environmental benefits, and would result in a 34% reduction in premature mortality. In another study, Springmann et al. (2018) analyse several options for reducing the environmental effects of the food system, including dietary changes towards healthier, more plant-based diets, improvements in technologies and management, and reductions in food loss and waste. They conclude that no single measure is enough to keep these effects within all planetary boundaries simultaneously, and thus a synergistic combination of all options will be needed.

2

Focus on Ireland’s Greenhouse Gas Emissions

Key messages

Ireland's and Europe's climate ambition has significantly increased since 2019.

Ireland's Climate Action and Low Carbon Development (Amendment) Act 2021 (Climate Act 2021) sets out in law the target of a 51% reduction in GHG emissions by 2030 relative to 2018 and a long-term national climate objective to "by no later than the end of the year 2050 … transition to a climate resilient, biodiversity rich, environmentally sustainable and climate neutral economy".

Progress has been made in reducing emissions since reaching a peak in 2005, but Ireland still has the second highest level of GHG emissions per capita across the EU. In 2021, carbon dioxide (CO_2) from energy accounted for most emissions (53%), while agriculture was the single largest source of GHG emissions (38%).

The limit on our greenhouse gas (GHG) emissions to meet reduction goals is determined by carbon budgets, which have been set for the periods 2021–2025, 2026–2030 and, provisionally, 2031–2035.

How each sector contributes to the overall emission reduction target is determined by individual sectoral emission ceilings. The setting of sectoral emission ceilings is a significant political milestone. However, currently, not all sectors are included. For example, the emission ceilings for the land use, land use change and forestry (LULUCF) sector have been deferred.

Ireland's emissions are going in the wrong direction. In 2021, they were 4 million tonnes above an indicative target based on the first carbon budget. Current polices will not be sufficient to stay within the carbon budgets for 2021–2025 and 2025–2030.

Previous estimates of Ireland's share of the 1.5°C carbon budget indicate that it is likely to be too late to stay within it.

This section introduces Ireland's GHG emissions and begins with an overview of current EU and national-level policy. This is followed by details of the sources of GHG emissions in Ireland, information on the most recent emission projections based on a continuation of current trends/policy, and finally a summary of our carbon budgets, which set key sectoral constraints to meet our overall emission reduction goal.

2.1 Policy landscape: setting the goals

Ireland's Climate Act 2021 represented a significant increase in its climate ambition. It sets out several critical legislative frameworks, including an interim emissions target for 2030, 5-yearly carbon budgets (2020–2025, 2026–2030 and 2030–2035), sectoral emissions ceilings, an annually updated climate action plan and a long-term climate action strategy. For a comprehensive assessment of Ireland's Climate Act 2021 see Torney (2021).

Under the Climate Act 2021, Ireland's national climate objective was set as follows:

The State shall, so as to reduce the extent of further global warming, pursue and achieve, by no later than the end of the year 2050, the transition to a climate resilient, biodiversity rich, environmentally sustainable and climate neutral economy. (Department of the Environment, Climate and Communications, 2021a).

This national climate objective replaced the national transition objective from the Climate Action and Low Carbon Development Act 2015. The revision to include "no later than the end year 2050" rather than "by 2050" strengthened the overall long-term commitment, while the interim target of a reduction in GHG emissions of 51% in 2030 relative to 2018 represents a significant increase in short-term ambition. This brings Ireland into line with the EU commitment to achieve climate neutrality by 2050, as enshrined in the European Climate Law of 2021. It now means that our short-term ambition actually exceeds the interim 'Fit for 55 package' (Figure 2.1).

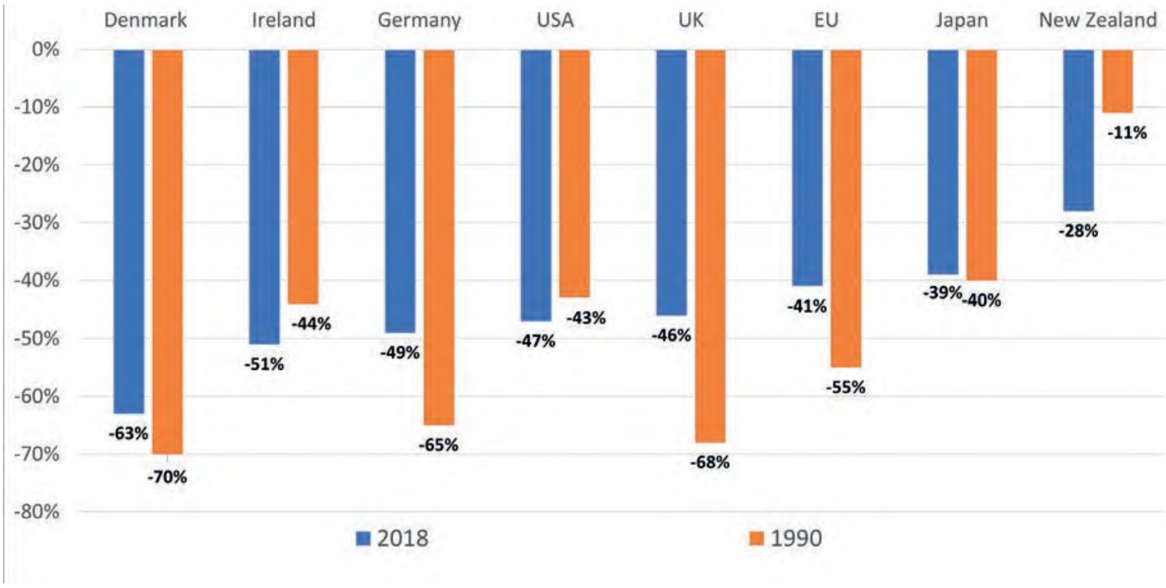


Figure 2.1 Comparison of EU and different country 2030 emission reduction targets relative to 1990 and 2018. Source: Authors.

The climate action plan is to be revised each year to ensure alignment with the legally binding carbon budgets and sectoral emission ceilings (section 2.4). The carbon budgets are a critical element of climate policy, bringing the long-term goal (for 2050) into near-term (annual) emission limits. For example, the first carbon budget (2021–2025) will require increased ambition over the next few years to counter the rebound in emissions seen in 2021 (sections 2.3.1 and 2.3.2).

There have been three climate action plans to date: the first published in June 2019 (Department of the Environment, Climate and Communications, 2019), the second published November 2021 (Department of the Environment, Climate and Communications, 2021b) and the third published in December 2022 (Department of the Environment Climate and Communications, 2022a). The actions set out reflect the growing ambition, particularly in the renewable energy targets set for 2030.

2.2 Ireland's historical emissions: how we got here

Ireland's historical CO_2 emissions differ from most other developed countries, with the rapid growth in activity that other nations experienced in the 1800s taking place from 1960 onwards (Figure 2.2). Following a peak in 2005, the economic downturn led to a fall in energy-related CO_2 emissions until recovery in 2012.

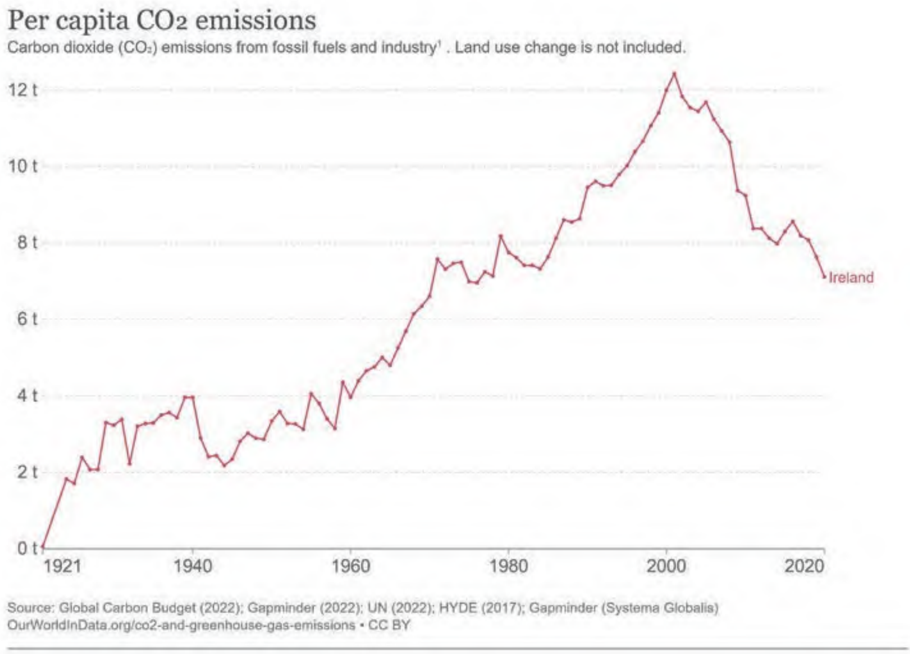


Figure 2.2 Ireland's CO_2 emissions 1920–2020 (Le Quéré et al., 2016)). Reproduction licensed under the Creative Commons Attribution CC BY-ND 3.0 licence (https://creativecommons.org/licenses/by-nd/3.0/).

The difference is quite apparent when looking at per capita emissions for the UK and Ireland. While the UK emissions peaked in the 1970s, and have since declined significantly, Ireland experienced a period of growth in emissions up until a peak in 2005 (Figure 2.3).

Figure 2.3 Ireland and UK CO_2 emissions per capita 1870–2020; based on Le Quéré et al. (2016) and Our World in Data (2020).

2.3 Current inventory: where we are now

Ireland's GHG emissions are reported annually by the Environmental Protection Agency (EPA) through the national inventory report submitted to the UNFCCC, which is the primary basis of the summary in this section.

2.3.1 Breakdown of Ireland's emissions in 2021

In 2021, total emissions of GHGs (without LULUCF, 7.8MtCO_2-eq) in Ireland were 62.1 MtCO_2-eq, up 5.2% from 59.06MtCO_2-eq in 2020 (EPA, 2023b). The total emissions including LULUCF were 69.4MtCO_2-eq. Between the period 1990 and 2021, Ireland's GHG emissions (excluding LULUCF) fluctuated at around 60MtCO_2-eq, with a low of 54.22MtCO_2-eq in 1990 and peak of 70.49MtCO_2-eq in 2005 (Figure 2.4).

While CO_2 is the most prominent gas, CH_4 from agriculture (due to enteric fermentation) represents the single largest source of emissions, accounting for 28.4% (excluding LULUCF) of total GHG emissions in 2021 (EPA, 2023b). This is the CH_4 belched by cows and sheep during the digestion of forage (primarily grass). In the rumen or forestomach of ruminant livestock there is a microbial ecosystem that allows them to obtain nutrition from plant matter, and biogenic CH_4 is a natural by-product of this process (Teagasc, 2022). The amount of agriculture GHG emissions is thus closely related to the number of livestock (see section 6.1.1).

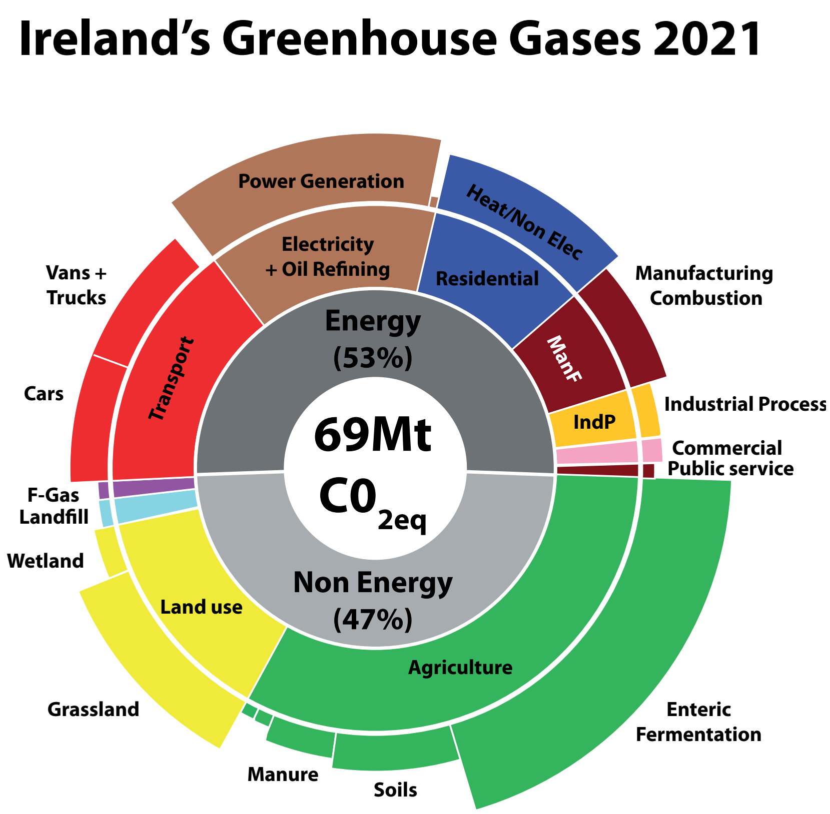


Figure 2.4 Ireland's GHG emissions in 2021, including LULUCF. F-Gas, fluorinated gas; IndP, industrial process; ManF, manufacturing; non elec, non-electric.

Looking at the types of emissions as opposed to the sources, we can see that emissions of CO_2 accounted for 37.5MtCO_2 (61%) of the national total GHG emissions in 2021 (excluding LULUCF), followed by CH_4 with 17.2MtCO_2-eq (28%) and N_2O with 6.1MtCO_2-eq (10%) (EPA, 2022f). The combined emissions of fluorinated gases (mostly emitted by hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride and nitrogen trifluoride) accounted for just 1% in 2021 (Figure 2.5).

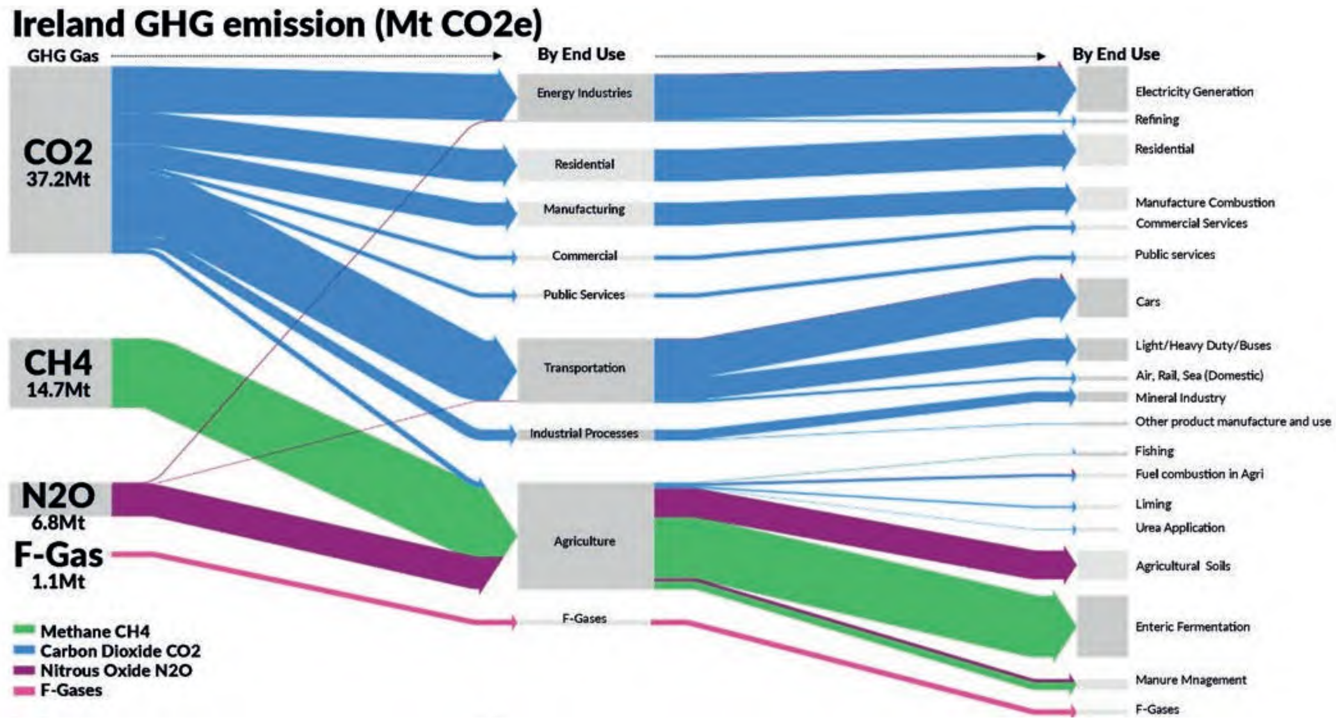


Figure 2.5 Ireland's GHG emissions ($MtCO_2$-eq) in 2019 by sector and end use; based on EPA (2021a).

Compared with other EU Member States, Ireland has higher than average emissions of CH_4 and N_2O because of its high agricultural contribution to national total emissions (Figure 2.6). Emissions per capita increased from a historical low of 11.8 tonnes CO_2-eq per person in 2020 to 12.3 tonnes CO_2-eq per person in 2021 (EPA, 2022a). Ireland's average emissions of GHG per capita between 2011 and 2021 was 12.8 tonnes (EPA, 2020a).

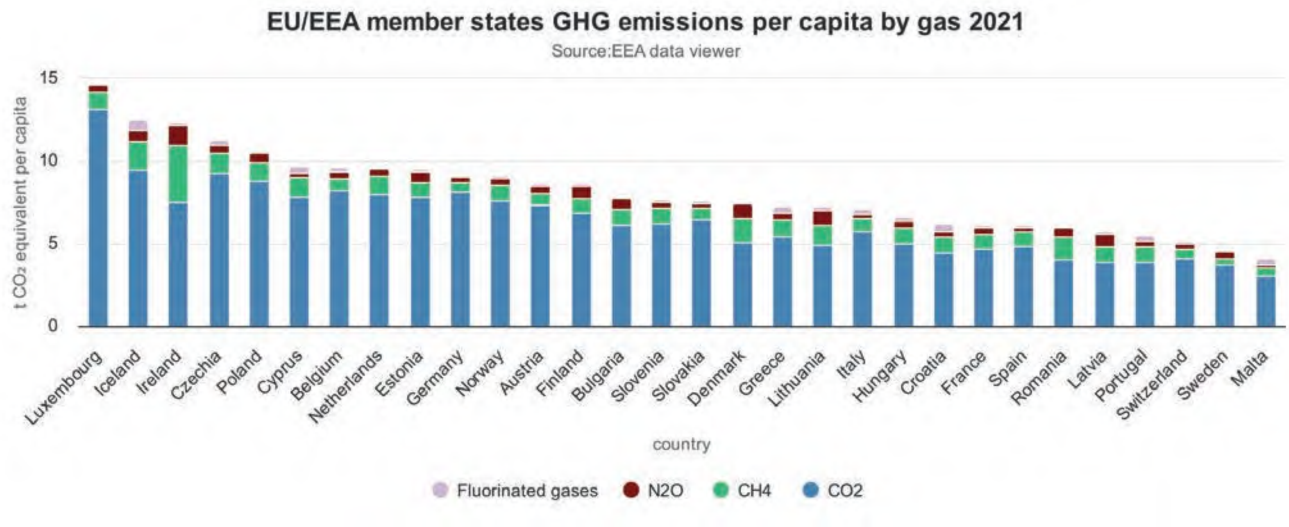


Figure 2.6 EU/European Economic Area Member States' GHG emissions per capita. Source: EPA (2022f).

2.3.2 Ireland's greenhouse gas emissions 1990–2021

As was the case globally, between 1990 and 2021, CO_2 was the most prominent GHG in Ireland, followed by CH_4 and then N_2O. Looking at how 2021 compares with 1990, emissions of CO_2 increased by 14%, CH_4 increased 9%, while N_2O decreased 7% (EPA, 2022b) (Figure 2.7).

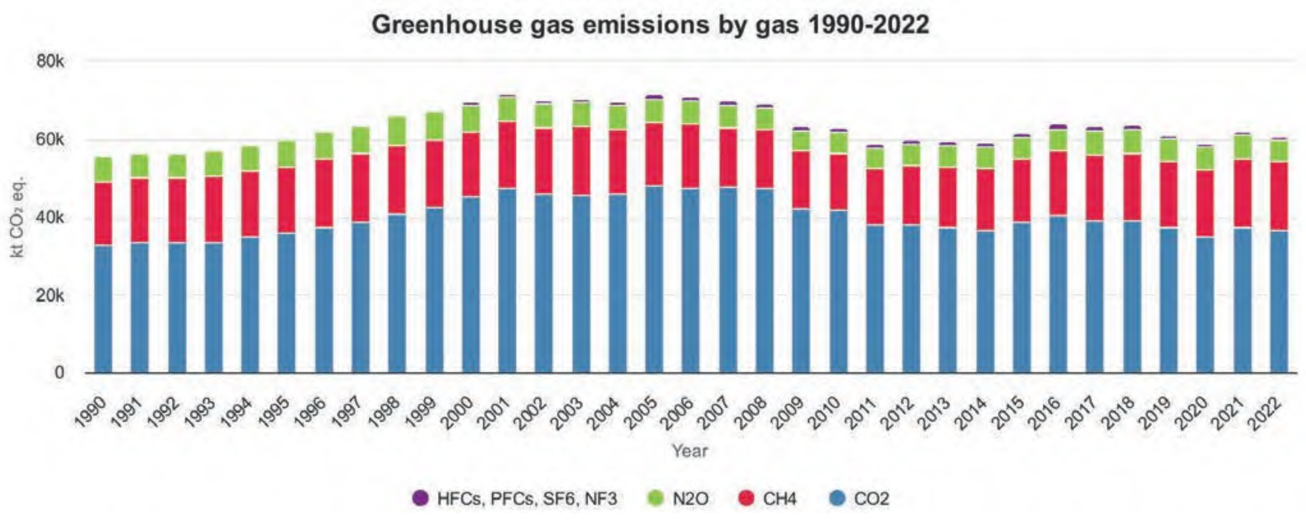


Figure 2.7 Ireland's total GHG emissions per gas (excluding LULUCF) 1990–2021. Source: EPA (2022e).

Like many other European countries, energy-related CO_2 (from energy industries, residential, manufacturing combustion, transport, commercial services and public services) accounts for most emissions. There was a marked increase in fuel use between 1990 and 2021 (EPA, 2022f): the most significant was in transport (112%), followed by the manufacturing industry and construction sector (13%). In contrast with other sectors, the emissions from energy industries were 9% below 1990 levels in 2021, reflecting a move away from fuels such as coal, peat and oil in electricity generation and higher levels of renewables (Gaffney et al., 2017). While residential emissions increased from 7.6MtCO_2 in 1990 to 9MtCO_2 in 2008, they decreased to 7MtCO_2 in 2021, a decrease of 7% relative to 1990 (Figure 2.8).

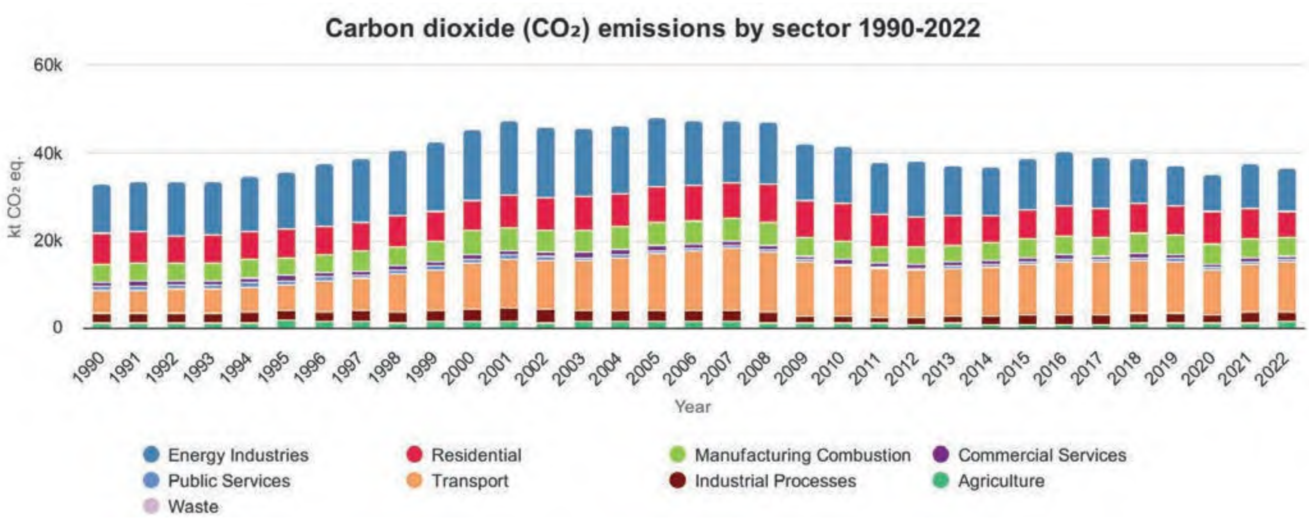


Figure 2.8 Ireland's total GHG emissions per sector (excluding LULUCF) 1990–2020. Source: EPA (2022e).

A summary of the trends in emissions by gas is provided in Annex A.7.

2.4 Our carbon budget: where we need to be

A carbon budget represents the total amount of emissions that may be emitted by a state (McGuire et al., 2020). It is generally a value for cumulative CO_2 emissions, with associated assumptions on the level of non-CO_2 emissions, i.e. the CO_2 budget will be lower when non-CO_2 emissions are higher and higher when non-CO_2 emissions are lower. Carbon budgets can also cover all GHG emissions and relevant sectors. In this case, they are measured in tonnes of CO_2 equivalent (CO_2-eq, see Box 1.1 and Box SPM.1 in Volume 1) and calculated on an economy-wide basis.

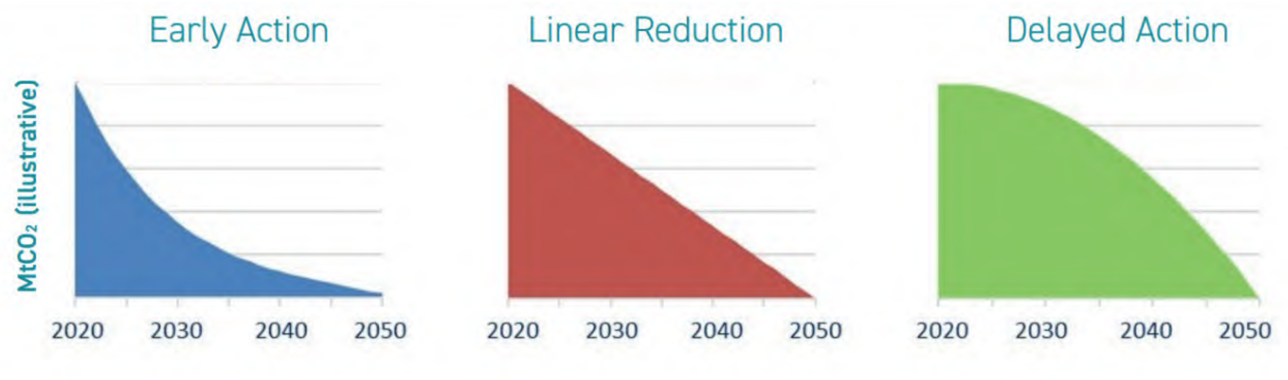


Figure 2.9 Impact of early and late action on cumulative GHG emissions. Source: McGuire et al. (2020).

Carbon budgets are a useful way of thinking about the pathway to net zero emissions. The three illustrative emission reduction pathways in Figure 2.9 all achieve net zero emissions in 2050, but the 'delayed' or Late action pathway has cumulative emissions that are double those of the Early action pathway's cumulative emissions, and therefore double the global warming impact. A carbon budget is the cumulative amount of GHG emissions permitted over a period to keep within a certain temperature threshold. Like a household budget, climate science sets a carbon budget for GHGs that can be 'spent' (emitted) for a given level of global warming. If we exceed this budget, then global temperatures will become higher.

2.4.1 Determining national carbon budgets

Global temperatures rise about 0.52°C for every 1 trillion tonnes of anthropogenic CO_2 that reaches the Earth's atmosphere (Volume 1). Van Vuuren et al. (2018) point to the simple strength of this near linear relationship in that:

- Long-term temperature does not depend on CO_2 emissions at a specific time.
- Near-term emissions are important as they also exhaust the carbon budget.
- CO_2 emissions will need to be phased out to net zero eventually to achieve temperature stabilisation.

This simple relationship between cumulative CO_2 emissions and temperature change (Box 1.1) is the reason that carbon budgets are such a powerful tool for succinctly understanding the impact of our energy system's pollution on the Earth's atmosphere.

The remaining cumulative CO_2 emissions that would result in a 1.5˚C or a 2˚C temperature increase with a given probability can be ascribed to a total carbon budget. See table 3.2 of IPCC WGII AR6 (Riahi et al., 2022). To return to below 1.5˚C warming by the year 2100, carbon budgets range from 320 to 400 billion tonnes of CO_2 ($GtCO_2$) from 2020 to 2100. To return to below 2˚C warming by the year carbon budgets range from 800 to 1,160$GtCO_2$ from 2020 to 2100.

To avoid raising the global average temperature by more than 2˚C, humans can collectively emit no more than 320–1,160$GtCO_2$. This then begs the questions: who gets to emit this remaining 1 trillion tonne carbon budget? How should this 1 trillion tonne carbon budget be shared among the 8 billion people, across generations and geographies globally?

There are several factors to be considered. If the 1 trillion tonnes were split 8 billion ways, then you get a figure of 125tCO_2 per person. To put this in perspective, the average Irish citizen emits roughly 7.5tCO_2 per year and so would have emitted their share by age 17 years. In addition, remember that a small proportion of the wealthiest countries in the world (USA, EU countries, Britain, Japan, Korea, and now China) have emitted the lion's share of the 2.2 trillion tonnes of CO_2 that have already warmed the Earth by over 1˚C (Kypreos et al., 2018).

There are multiple methods for allocating the remaining global carbon budget to national carbon budgets based on rules utilising a collection of historical, environmental and socioeconomic metrics. These allocation rules are complex, based on judgement and have been discussed since the very beginning of the UNFCCC in 1992. Each of these rules is implicitly biased towards or against countries based on their stage of economic development and their historical cumulative emissions, which largely is a function of which countries industrialised first and how efficiently they have turned carbon energy into capital wealth.

The following are some of the metrics-based rules that are used in the academic literature to explore the impacts of allocating the global carbon budgets to countries (McGuire et al., 2020):

1. **Grandfathering** is an interpolation rule whereby each country's emissions converge on a global average at some point in the future. This enables low-level emitters to raise their per capita emissions, while it gives time to high per capita-emitting countries to contract their per capita emissions to a global average. Typically, the grandfathering rule is seen to be systematically biased towards high-emitting countries, as it allows them to emit a disproportionately large share of the global carbon budget (Kartha et al., 2018; Rajamani et al., 2021).
2. **Brazilian rule** is a simple rule whereby each country is allocated a per capita weighted share of the total cumulative carbon budget, including historical cumulative emissions and the remaining 1.5˚C or 2˚C carbon budget. This rule is seen as political and economically untenable, as the wealthiest countries in the world have far exceeded their per capita share of the total 3 trillion tCO_2 carbon budget to stay below 1.5˚C. The Brazilian rule is hugely sensitive to the start year of the historical cumulative emissions budget, be that 1751 or 1990.
3. **GHG development rights** allocation rules are based on the principles of capacity to pay and responsibility for paying enshrined within the Paris Agreement. These rules aim to enable minimum levels of development in developing and emerging economies, whereby these countries receive investment and aid in proportion to the carbon budget value (as a function of the global social cost of carbon) that they are unlikely to be able to utilise for development and wealth creation within the constraint of a global 1$GtCO_2$ cap enforced on the global atmospheric commons.
4. **Ability to pay** allocates national carbon budgets based on a country's energy system resources, ability and cost efficiency to transition to net zero while minimising the economic cost or burden to the economy as a whole. The ability to pay carbon budget allocation rules aims to optimise the global energy system at the least cost while equalising the cost per capita of the energy transition or equalising the share of gross domestic product (GDP) spent per country on the energy transition globally.

Pye et al. (2017) (UK) and Glynn et al. (2019) (Ireland) were the first publications to assess the impact of carbon budget allocation rules on their national energy systems pathways towards a net zero energy system, and the impact of the grandfathering and Brazilian rule scenarios are explored in detail. Their analyses show the resulting energy system development pathways, costs, investments and rates of change to the energy system that is required to achieve the Paris Agreement goals fairly and equitably (see further outline in Chapter 7).

2.4.2 Estimates of Ireland's carbon budget

Glynn et al. (2019), in their assessment of zero carbon energy system scenarios, determine the cumulative carbon budget for Ireland to range from 128 to 766MtCO_2 for the period 2015–2070. This is derived from the Irish population share (0.064%) of the global population and taking the same 0.064% share of the remaining global carbon budgets. The global carbon budget varies based on temperature goal and probability, for example a 66% probability of achieving a 2°C limit or a 50% probability of reaching a 1.5°C limit. They note that 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, unlike other developed nations that industrialised earlier (section 2.2), Ireland is not in significant carbon debt (Gignac and Matthews, 2015; Le Quéré et al., 2016); Irish historical CO_2 emissions from fossil fuel combustion and cement production from 1751 to 2015 are estimated at approximately 2.04GtCO_2 (Le Quéré et al., 2016), which is less than 0.064% of 3,200GtCO_2, the Irish per capita share of the all-time global carbon budget for 2°C. This 3,200GtCO_2 figure is based on the historical emissions range of 2,200GtCO_2 (±257GtCO_2) from the global carbon project (Le Quéré et al., 2016) added to the remaining central 2°C budget of 1,000GtCO_2 from Friedlingstein et al. (2014). For discussion of the remaining global carbon budget, see Volume 1.

This is not the only carbon budget calculated to date for Ireland. McMullin et al. (2020b) determine Ireland's 'fair share' of the remaining global carbon budget to have been 391MtCO_2, equal to 83tCO_2 per capita, from 2015. In an EPA research report into negative emission technologies, McMullin et al. (2020a) determined a prudent, equitable, Paris Agreement-aligned remaining CO_2 quota for Ireland to be approximately 400MtCO_2 from 2015 or 180MtCO_2 from 2020. These estimates are based on a 'population-sharing' methodology derived from Raupach et al. (2014). A report from McGuire et al. (2020) provides four carbon budgets based on different effort-sharing methodologies: the Regensburg model and the extended smooth pathway model. The Regensburg model is primarily based on the contraction and convergence approach, while the extended smooth pathway model is based on a weighted distribution of population, which is the equality approach, and emissions, which is the grandfathering approach. To account for non-CO_2 emissions (CH_4 and N_2O), McMullin and Price (2020a) apply a GWP* methodology for what they call 'a prudent Irish fair share quota' of the remaining global cumulative GHG budget within the Paris Agreement temperature goals, estimated at approximately 540MtCO_2-we (warming equivalent) from 2015. At current emission levels, this would be fully depleted by about 2025. Continuing net positive (CO_2-we) annual emissions beyond that will result in national quota overshoot, which will have to be capped as quickly as possible and then reversed, potentially implying very large-scale removal of CO_2 from the atmosphere (section 4.11.2 and summary of the analysis in Annex A.3.3).

Table 2.1 *Ireland's emissions since the Paris Agreement 2015–2021*

	2015–2021	2020 and 2021
Total emissions ($MtCO_2$-eq)	483	135
CO_2 emissions ($MtCO_2$)	311	86

Source: EPA (2022f).

Ireland has continued to have relatively high emissions since 2015 (Table 2.1). Based on previous estimates of Ireland's fair share of the 1.5°C budget, it has thus either already been exceeded or is very nearly spent (Table 2.2).

Table 2.2 *Range of Irish carbon budget estimates*

Start year	Irish carbon budget ($MtCO_2$)	Effort-sharing methodology (global carbon budget)	Source
2020	180	Population sharing (610$GtCO_2$, 66% probability of 2°C)	McMullin et al. (2020a)
	225	Extended smooth pathway model (279$GtCO_2$, 1.5°C)	McGuire et al. (2020)
	251–263	Regensburg model (279$GtCO_2$, 1.5°C)	McGuire et al. (2020)
	368	Equitable population weighted (590$GtCO_2$, 66% probability of 2°C with high non-CO_2)	Glynn et al. (2019)
	638	Equitable population weighted (1,000$GtCO_2$, 66% probability of 2°C with low non-CO_2)	Glynn et al. (2019)
	734	Extended smooth pathway model (909$GtCO_2$, 2°C)	McGuire et al. (2020)
2015	128	Equitable population weighted (200$GtCO_2$, 66% probability of 1.5°C)	Glynn et al. (2019)
	223	Equitable population weighted (350$GtCO_2$, 50% probability of 1.5°C)	Glynn et al. (2019)
	391	Population sharing (610$GtCO_2$, 66% probability of 2°C)	McMullin et al. (2020b)
	400	Population sharing (610$GtCO_2$, 66% probability of 2°C)	McMullin et al. (2020a)
	540*	GWP* methodology to reflect a prudent Irish 'fair share quota' (844$GtCO_2$, 66% probability of 2°C)	McMullin and Price (2020a)
	766	Equitable population weighted (1,200$GtCO_2$, 66% probability of 2°C)	Glynn et al. (2019)

*$MtCO_2$-we.

2.4.3 Ireland's carbon budgets

The Climate Change Advisory Council is responsible for proposing the 5-year economy-wide carbon budgets, to assist the state in achieving its national climate objectives and GHG emissions targets agreed by the EU. The first three carbon budgets cover the following 5-year periods: 2021–2025, 2026–2030 and 2031–2035 (although the budget for the third period is provisional). They are as follows (Climate Change Advisory Council, 2021):

- 2021–2025: 295MtCO_2-eq an average of –4.8% per annum for the first budget period.
- 2026–2030: 200MtCO_2-eq an average of –8.3% per annum for the second budget period.
- 2031–2035: 151MtCO_2-eq an average of –3.5% per annum for the third provisional budget.

In line with government legislation (Climate Act 2021), the carbon budgets proposed for 2021–2025 and 2026–2030 are to provide for a reduction of 51% in the total amount of GHG emissions from 2018, including LULUCF.

There was a limited body of evidence for the Climate Change Advisory Council to draw from (Table 2.2). The approach taken to calculate the carbon budgets from the bottom-up was as follows (Climate Change Advisory Council, 2021):

1. The 51% reduction in emissions target is used to calculate the required level for total emissions in 2030, which is 33.5MtCO_2-eq.
2. Modelling of the energy system, agriculture and land use by University College Cork, Teagasc and University of Limerick illustrated the amount of GHGs that would be emitted on different pathways towards meeting the overall 51% target by 2030.
3. The amount of emissions allowed from each sector was aggregated for each scenario to give an economy-wide total for the scenario in each budget period. The total emissions from each economy-wide scenario were then averaged to give the final carbon budget amounts.

Unlike the majority of the estimates presented in section 2.4.2, Ireland's carbon budgets include both CO_2 and non-CO_2 gases (CO_2-eq). Under Ireland's Climate Act 2021, the Council was to consider CH_4 as part of the overall mix of GHGs using GWP_{100} (Climate Change Advisory Council, 2021). Other metrics, such as GWP*, may offer a closer resemblance between cumulative CO_2-eq emissions and temperature change, but, at present, GWP_{100} is the metric most commonly used for international accounting (see Volume 1, section 2.3.4). As raised by the Council and noted in Box 1.1, this is important with regard to defining the long-term goal of climate neutrality.

2.4.4 Sectoral emissions ceilings

The contribution of each sector to the overall carbon budgets is determined by sectoral emission ceilings, they are approved by government and the act provides for each minister to be accountable in this regard. These recognise that some sectors will do a lot more than others. Under Section 6C of the Climate Act 2021, sectoral emission ceilings required Cabinet approval (Department of the Taoiseach, 2022). This means that each of the departments have agreed to the target set for its sector.

The sectoral ceilings were approved in July (Department of the Taoiseach, 2022) and later released in September 2022 (Table 2.3).This is an important milestone. However, it is only the beginning of a very long journey, and there are two key issues with the current figures:

1. Not all sectors are currently included. Finalising the sectoral emission ceilings for the LULUCF sector has been deferred until after the completion of the land use strategy (Department of the Taoiseach, 2022).
2. The numbers do not add up to the overall target. As highlighted in the Climate Change Advisory Council Annual Review 2022, the quantified emissions reductions amount only to a reduction of 42% excluding the LULUCF sector, and are therefore not consistent with the objective in the Climate Act 2021 (Climate Change Advisory Council, 2022).

> *"Ireland has continued to have relatively high emissions since 2015 (Table 2.1). Based on previous estimates of Ireland's fair share of the 1.5°C budget, it has thus either already been exceeded or is very nearly spent (Table 2.2)."*

Table 2.3 *Sectoral emission ceilings, as published 20 September 2022*

Sector	2018 Baseline ($MtCO_2$-eq)	Sectoral emission ceilings for each 5-year carbon budget period ($MtCO_2$-eq)		Indicative emissions in final year of 2021–2025 carbon budget period ($MtCO_2$-eq)	Indicative reduction in emissions in final year of 2021–2025 budget period compared with 2018	Emissions in final year of 2026–2050 carbon budget period ($MtCO_2$-eq)	Reduction in emissions in final year of 2026-2030 carbon budget period compared with 2018	Agreed CAP21 ranges
	2018	**2021–2025**	**2026–2030**	**2025**	**2025**	**2030**	**2030**	**2030**
Electricity	10	40	20	6	~40%	3	~75%	60–80%
Transport	12	54	37	10	~20%	6	~50%	40–50%
Built environment – residential	7	29	23	5	~20%	4	~40%	45–55%
Built environment – commercial	2	7	5	1	~20%	1	~45%	
Industry	7	30	24	6	~20%	4	~35%	30–40%
Agriculture	23	106	96	20	~10%	17.25	~25%	20–30%
LULUCF	5	XXX	XXX	XXX	XXX	XXX	XXX	40–60%
Other (F-gases, waste and petroleum refining)	2	9	8	2	~25%	1	~50%	N/A
Unallocated savings			–26			–5.25		
TOTAL	68	XXX	XXX	XXX	XXX	XXX	XXX	N/A
Legally binding carbon budgets and 2030 emission reduction targets	–	295	200	–	–	34	51%	–

Note: Figures for emissions ($MtCO_2$-eq) for 2018 and 2020 have been rounded, which may lead to some discrepancies. CAP21, Climate Action Plan 2021.

Source: Government of Ireland (2022b).

2.5 Projections: where we are going

The GHG emissions rebound in 2021 (section 2.3) meant that emissions were 4 million tonnes above an indicative target based on first carbon budget (Figure 2.10). If emissions continue to be above the indicative pathway shown, then there will be an increased burden on later years to decrease emissions more dramatically.

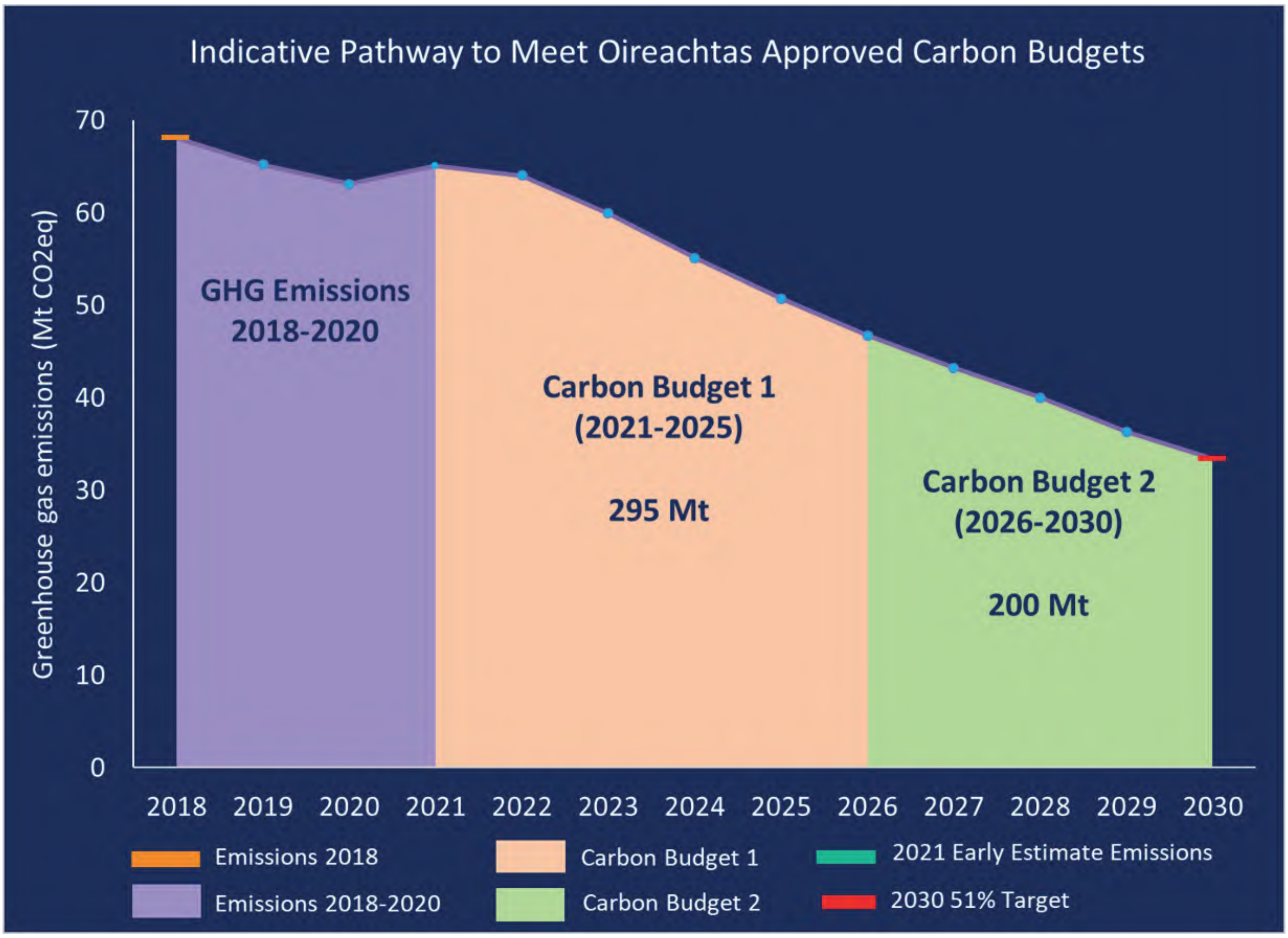


Figure 2.10 Pathway consistent with first two carbon budgets (2021–2025 and 2026–2030).

In Ireland, official national emissions projections are published annually by the EPA (EPA, 2022d) (Figure 2.11). There are two scenarios explored: a with existing measures (WEM) scenario and a with additional measures (WAM) scenario:

- The WEM scenario assumes that no additional policies or measures are implemented, beyond those already in place by the end of the previous year (latest national GHG emission inventory).
- The WAM scenario assumes that in addition to the existing measures, there is also full implementation of planned government policies and measures to reduce emissions such as those in the Climate Action Plan 2021.

The most recent projections for emissions from 2021 to 2040 had the following highlights (EPA, 2022d):

- Existing policy measures will not be sufficient to meet the carbon budgets.
    - o Budget 1 – In the WEM scenario, this is projected to be exceeded by 55MtCO_2-eq, and in the WAM scenario by 40MtCO_2-eq.
    - o Budget 2 – In the WEM scenario this is projected to be exceeded by 127MtCO_2-eq, and in the WAM scenario by 77MtCO_2-eq.
    - o Budget 3 – In the WEM scenario this is projected to be exceeded by 166MtCO_2-eq, and in the WAM scenario by 94MtCO_2-eq.

- Ireland can meet its non-Emissions Trading System (ETS) EU targets of a 30% emission reduction by 2030 (compared with 2005), assuming implementation of planned policies and measures and the use of the flexibilities available.
- The gap between the WEM and WAM scenarios in these projections highlights that the current pace of implementation will not achieve the change required to meet the Climate Act 2021 targets. Faster implementation of 'additional measures' is needed to close this gap.
- A CH_4 emissions reduction of almost 30% is required to achieve a 22% reduction in agricultural emissions compared with 2018, as committed to in the Climate Action Plan 2021 (which is less than the 25% reduction later agreed in sectoral ceilings, see section 2.4.4). The sector must clearly set out how this will be achieved to address uncertainty regarding its ability to deliver even the lower end of the range of its sectoral targets within the ever-shortening timeframe to 2030.

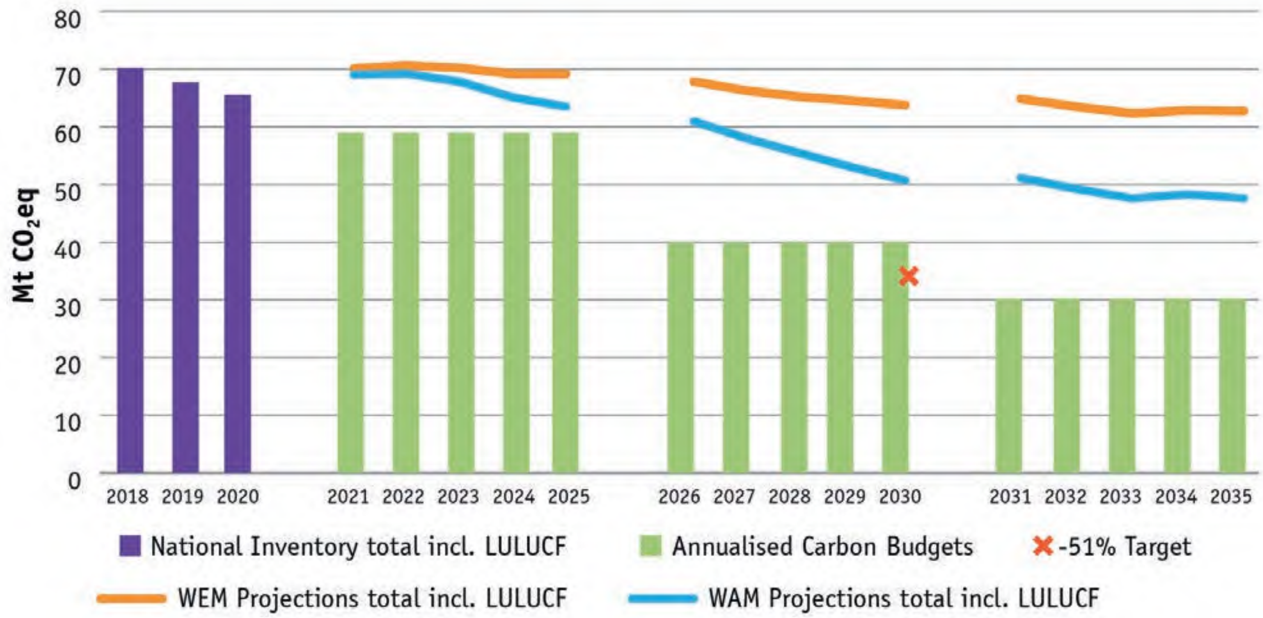


Figure 2.11 Annualised carbon budgets (2021–2025, 2026–2030, 2031–2035) and projected emissions data ($MtCO_2$-eq) (including LULUCF) under the WEM and WAM scenarios. Source: EPA (2022d).

3

Ireland's Energy System Today

Key messages

The energy system can be understood as a balance between demand in the form of services we need (e.g. heat, mobility) and the supply of energy to meet them (e.g. oil, electricity).

Ireland is currently heavily reliant on imported fossil fuels, accounting for 87.5% of our energy in 2021.

Oil (diesel, kerosene and petrol) accounts for nearly half of Ireland's energy supply.

The transport sector has the largest energy demand followed by residential buildings, commercial services and industry.

Most progress to date in renewable energy has been with renewable electricity, through the significant deployment of onshore wind energy. Heating and transport are lagging behind.

Improved energy security is an important co-benefit of increased levels of indigenous renewable energy. However, realising this opportunity will require substantial upgrades to Ireland's electricity grid.

3.1 What is the energy system?

Energy is a vital aspect of our society. It impacts every aspect of our daily life: lighting and heating our homes, how we get around, enabling our work, and powering our hospitals and other essential services. There are significant challenges to reducing the environmental impact of the energy we use, while at the same time providing a decent standard of living for all.

The energy system is defined broadly to include both physical and societal dimensions. The physical dimension includes all the infrastructure (e.g. roads, pylons, pipelines) and equipment (e.g. cars, heaters, appliances, power plants) used to mine, convert, transport and transmit to provide energy services. In addition to this physical dimension, there is a broad range of societal dynamics that are relevant to the energy system. To understand these, it is useful to think about the services that energy provides, such as transport for ourselves and the goods that we consume, heating or cooling, cooking and lighting.

The impact on our lives needs to be considered together with technical solutions when planning for the transition of our energy system away from fossil fuels. Moreover, this transformation of energy systems must be reconciled with both the UN Sustainable Development Goals and the inertia of the existing fossil fuel energy infrastructure (Davis et al., 2018).

Looking at the example of our electricity system, the changes can be viewed within the context of longer-term trends in energy supply and demand (Figure 3.1). Over the past century, Ireland's electricity sector has undergone a significant transformation. Through the foundation of the State, world wars, and energy crises, the sector has continually expanded, bringing affordable electricity to the most rural parts of the country. The establishment of a national organisation (Electricity Supply Board or ESB) to bring together small undertakings under one roof to build, maintain and continually develop the sector is common across developed countries. The struggles of many to improve security of supply during and after the 1970s oil crises is also well documented. However, Ireland's evolution differs from that experienced in many other countries due to its geographically isolated position on the periphery of Europe, its lack of fossil fuel resources and its own geopolitical unrest (Gaffney et al., 2017).

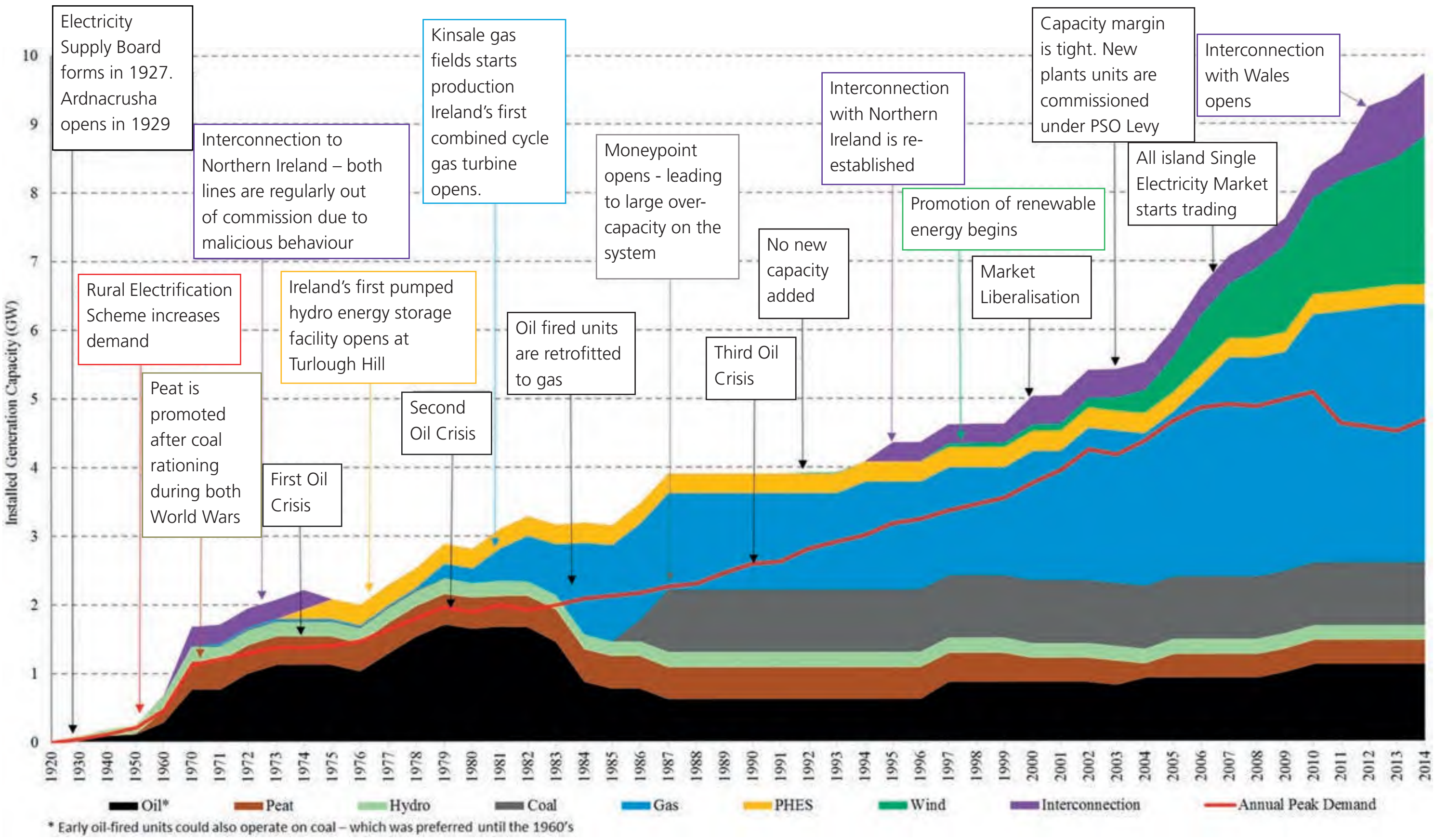


Figure 3.1 100 years of electricity development. Source: Reproduced from Gaffney et al. (2017) with permission from Elsevier.

Ireland's energy system and indeed the global energy system of the future will be very different from those of today if the world is successful in limiting warming to well below 2°C or to 1.5°C. Energy will be provided in different ways, converted in different ways and used in different ways. Achieving and responding to these changes presents an impressive range of challenges and opportunities, as discussed in this chapter.

3.2 Ireland's current energy system

Ireland's energy system is still heavily reliant on imported fossil fuels, which represent 87.5% of Ireland's energy supply in 2021 (SEAI, 2022c). Looking at the flow of energy in Ireland's energy system in 2019 (used as reference year due to COVID-19 impacts in 2020 and 2021), oil and natural gas are the dominant fuels on the supply side, while the two largest sources of energy demand are homes and private travel (Figure 3.2).

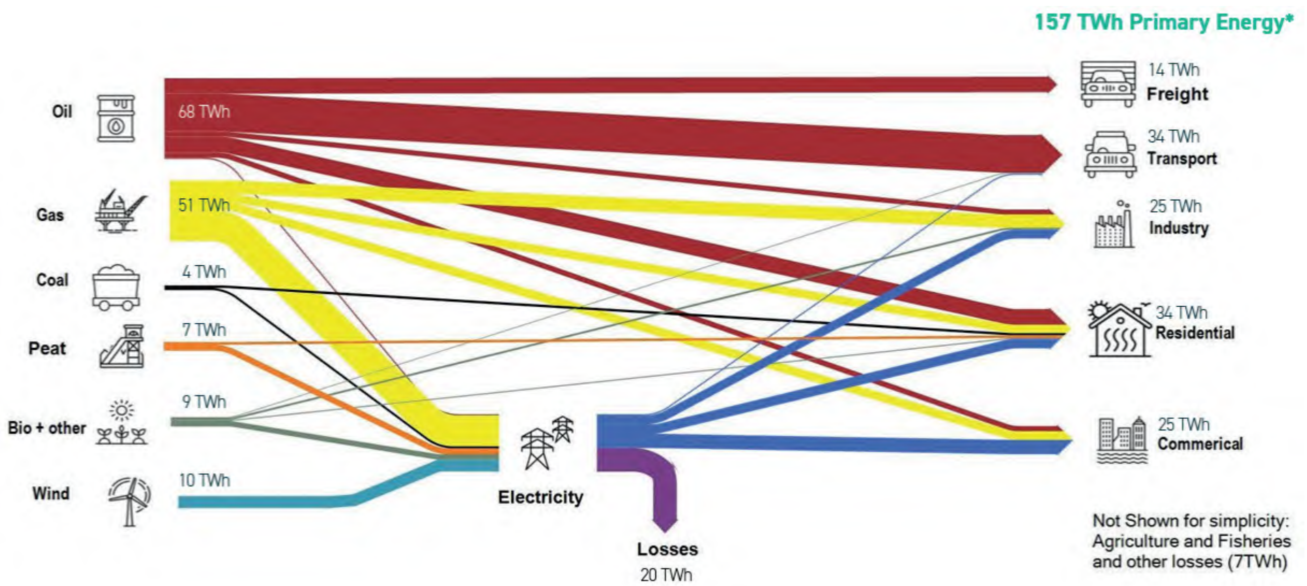


Figure 3.2 Ireland's energy system in 2019. Source: Deane et al. (2021b). *Primary energy shown. Excludes international aviation and shipping.

Ireland's total final energy consumption fluctuated at around 11,000ktoe between 2011 and 2021. The Sustainable Energy Authority of Ireland (SEAI) generally uses the unit ktoe (kilotonnes oil equivalent) in its reporting of Ireland's energy balance (energy demand and supply), to align with standardised Eurostat and IEA reporting practices (SEAI, 2021c). It is thus used here and in the following sections, which are primarily based on SEAI's Energy in Ireland: 2022 Report (SEAI, 2022c) and energy balance (SEAI, 2022g). The conversion rate is 1ktoe = 11.63MWh (SEAI, 2022f).

3.3 Fossil fuels in Ireland's current energy system

Ireland still relies largely on fossil fuels for its energy supply. In 2019, we ranked fifth for fossil fuel dependence across Europe. Recent trends in Ireland's fossil fuel use show a decline in oil, coal and peat, but an increase in natural gas (Figure 3.3). This has been primarily due to changes in electricity generation.

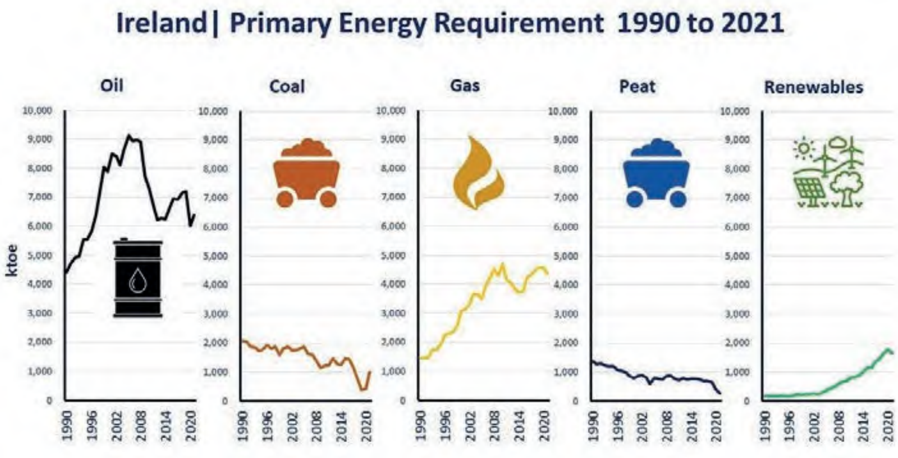


Figure 3.3 Energy supply trends in Ireland 1990–2020.

3.3.1 Oil

Oil is currently Ireland's dominant energy source (Figure 3.4). It accounted for 45% of primary energy in 2021 at 6,012ktoe (SEAI, 2022g). Diesel in transport, at 2,891ktoe, accounted for 48% of oil final energy consumption in 2021. The next largest demand was heating oil in the residential sector at 1,223ktoe (21%), followed by petrol in transport at 613ktoe (10%) (SEAI, 2022g).

Apart from a small amount of indigenous biofuel production, Ireland imports all of its oil. Ireland's only oil refinery is in Whitegate, Co. Cork, which provides 30–40% of Ireland's oil demand (SEAI, 2020c). The sources of the crude oil imported to Whitegate between 2005 and 2018 were mainly Norway, Denmark and the UK. The remainder of the country's demand was met from imports of refined products (i.e. diesel, petrol), 64% of which came from the UK in 2018. Given Ireland's dependence on imported oil, the oil terminals and storage facilities on the island of Ireland are particularly important from a security of supply perspective (SEAI, 2020c). Oil is imported via the six principal oil ports at Dublin, Whitegate (Cork), Foynes (Limerick), Galway, Derry and Belfast. Oil products are imported by ship, unloaded to storage tanks at the ports and then distributed by road. Ireland has no oil distribution pipelines. Biofuels are imported as either blended or unblended product.

The dominance of oil in Ireland's transport sector, in the form of petrol and diesel, presents a key challenge for the next decade. An increasing proportion of it will be displaced by biofuels (section 4.5.3) and the move to electric vehicles (EVs) (section 4.4.1). In heating, improvements in energy performance (section 5.1), heat pumps (section 4.4.2), biogas injection into the gas grid (section 4.5.2) and biomass (section 4.5.1) may reduce Ireland's dependence on oil.

3.3.2 Solid fuels

3.3.2.1 Coal

Coal and (to a lesser extent) peat continue to fuel electricity generation in Ireland. Under the National Development Plan 2018–2027, the government set the target of ending the burning of coal in Moneypoint, which is Ireland's only coal-fired electricity generation plant, by 2025 (Government of Ireland, 2018a). Moneypoint is important for the operation of the grid, as what is known as a base load generator, constantly covering a large share of our electricity demand. Its three 305MW

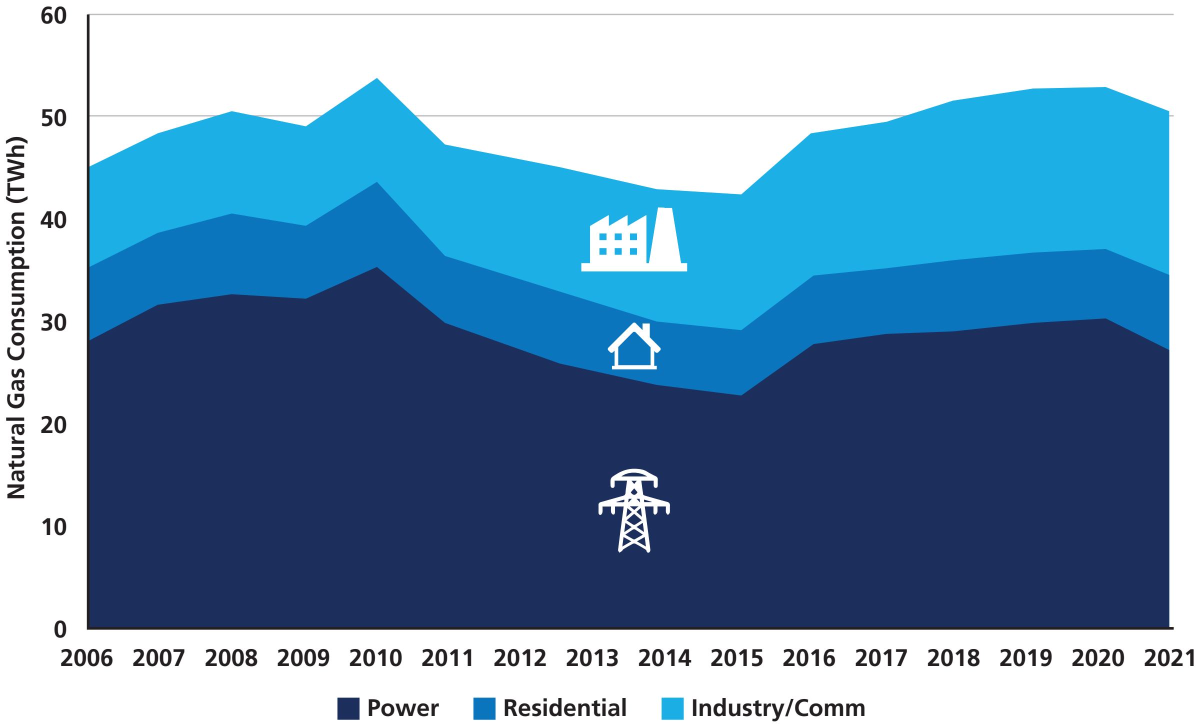


Figure 3.4 Annual natural gas demand in Ireland by sector 2006–2021. Source: SEAI (2022g).

generators (915MW total) can provide up to 7TWh per year (ESB, 2016), which is equivalent to the annual electricity demand of 1.39 million homes[14]. However, in recent years, the amount of coal generation has fallen. In 2020, coal accounted for just 2% of generated electricity compared with 23% in 2005 (SEAI, 2021c). However, outages in plants (Huntstown and Whitegate) and lower wind levels led to a rise in coal generation in 2021, providing 8.2% of the electricity generated (SEAI, 2022c). This means that the carbon intensity of Irish electricity remains one of the highest in the EU, despite all our progress in using renewable energy (section 3.4.1).

There is also still a small amount of coal burnt for home heating (185ktoe). The burning of smoky coal in areas designated as low-smoke zones is prohibited, which was first introduced in Dublin in 1990 and extended to other cities and large towns since. As of September 2020, the ban covers all towns with populations exceeding 10,000 people. In July 2022, the government reached agreement on a nationwide ban on smoky solid fuels (smoky coal, turf and wet wood) (Department of the Environment, Climate and Communications, 2022b). The ban on smoky fuels is due to their contribution to air pollutants (Harrington et al., 2020). Particulate matter (mainly $PM_{2.5}$) from the burning of solid fuels and traffic exhausts results in around 1,300 premature deaths per year in Ireland (Byrne, 2021). The dominant source of $PM_{2.5}$ emissions in Ireland is the combustion of fossil fuels in residential and commercial and manufacturing industries, and in the construction industry, which produced 53.1 % and 11.6% of the annual total, respectively, in 2021 (EPA, 2023a).

3.3.2.2 Peat

As in the case of coal, historically, peat was mostly used for electricity generation. For most of the last two decades, peat-fired power generation was supported by a Public Service Obligation levy on electricity consumers. This policy supported the use of indigenous fuel for electricity generation and contributed to employment in the Midlands region. With a commitment to move away from peat, the support was phased out by the end of 2019. In 2020, two of Ireland's three peat power plants closed (ESB, 2021). The final remaining peat power station was due to close in 2023 when its planning permission expired (Bord na Móna, 2021b); however, planning permission has been awarded and the plant will continue operating until 2030, running on 100% biomass from 2024 (EirGrid, 2022).

[14] Based on 5,028kWh/home/year,; see table 34 in SEAI (2021c).

The remaining peat use is in heating in the residential sector. SEAI estimates that approximately two-thirds of peat use in the residential sector in 2018 was sod peat, with briquettes accounting for one-third (SEAI, 2018a). The ban on smoky solid fuels introduced in 2022 prevents the sale of commercial peat. However, this covers only a very small fraction of peat use. Eakins et al. (2022) estimate that over 90% of sod peat consumption is non-traded, meaning that it comes from either people's own bogs or is traded locally without a commercial licence.

All of Ireland's peat for energy purposes is indigenously produced (SEAI, 2020c). Commercial peat harvesting in Ireland is managed by Bord na Móna, founded by the state in 1946. In 2018, the Brown to Green strategy began a change of direction away from carbon-intensive activities (Bord na Móna, 2021a). Following a High Court ruling in 2019 that peat harvesting on bogs over 30 hectares requires planning permission, Bord na Móna subsequently suspended peat harvesting in 2020 and formally announced an end to all harvesting at the beginning of 2021 (Bord na Móna, 2021b). Peatlands cover 1.03 million hectares of the country. Under Articles 2 and 4 of the EU Habitats Directive, Ireland is obliged to protect and, where possible, restore peatlands/boglands.

3.3.3 Natural gas

In 2021, natural gas accounted for 34% of Ireland's primary energy, at 4,564ktoe. It is an important fuel for generating electricity and heating. The gas grid is 14,400-km long across 21 counties, serving over 700,000 gas customers, including 30,000 businesses (Gas Networks Ireland, 2019). When combusted, natural gas is the least carbon-intensive fossil fuel. However, the leaking of CH_4 (a much more damaging GHG) during production and transport is a concern. The CH_4 leakage rate in Ireland is quite low because there is a limited amount of extraction and we do not have large-scale pipelines. In 2020, natural gas leakage accounted for 2.4% of CH_4 emissions (EPA, 2022e). Unlike the demand for solid fuels, which is in decline, we are still increasing gas demand. Between 2017 and 2021, over 45,000 new consumers were connected to our gas infrastructure, which amounts to around 4,000GWh of new gas demand (SEAI, 2022c).

Most of our natural gas demand is for electricity generation. There has been growing demand for gas power plants to manage the increases in electricity demand, primarily driven by large new energy users (data centres) (section 4.3.1). However, power plant outages in 2021 meant that gas provided 46% of our electricity, compared with 51% in 2020 (SEAI, 2021c, 2022c). Gas plays a particularly important role in facilitating the integration of wind, solar and other intermittent or variable renewable electricity sources. When production from these sources is low, gas production can quickly ramp up to fill the gap, much more so than fuels like coal. In industry, gas has proven to be cheaper and cleaner than previous alternatives. Large quantities of energy can be moved through the gas network efficiently, and gas boilers and combined heat and power plants offer high efficiency, leading to lower overall emissions than if coal, oil or other fuels were used (Figure 3.4).

Ireland's primary gas field is Corrib. In 2021/2022 (October 2021 to September 2022), indigenous gas sources met 27% of annual gas demand (Corrib and a very small amount of biomethane), while the balance of 73% was imported from the UK through the Moffat entry point (Gas Networks Ireland, 2022b). Ireland's indigenous gas supplies have been in decline. Over the same period in 2017/2018, indigenous gas sources met 63% of Ireland's annual gas demand (Corrib covering 57% and

Inch 6%), leaving a balance of 37% being imported from the UK through the Moffat entry point (Gas Networks Ireland, 2018). Ireland's indigenous gas supply (Corrib) is expected to decline quickly during the 2020s. This will make us more reliant on imports through the interconnector system with the UK, which itself imports almost half of its gas via pipeline from European neighbours and as liquefied natural gas from further afield (section 3.5).

3.4 Renewables in Ireland's current energy system

In 2020, SEAI estimate that 6.5 million tonnes of CO_2 emissions were avoided by the use of renewables in Ireland (SEAI, 2021f). There are many benefits to increasing the use of renewables. Increasing Ireland's use of renewable energy will reduce GHG emissions and some types of air pollution by replacing fossil fuels. Adding renewable energy diversifies the national energy supply and helps reduce Ireland's dependence on imported fuels. In addition, the manufacture, installation and maintenance of renewable energy infrastructure can stimulate and drive economic activity in Ireland (Volume 4) (Figure 3.5).

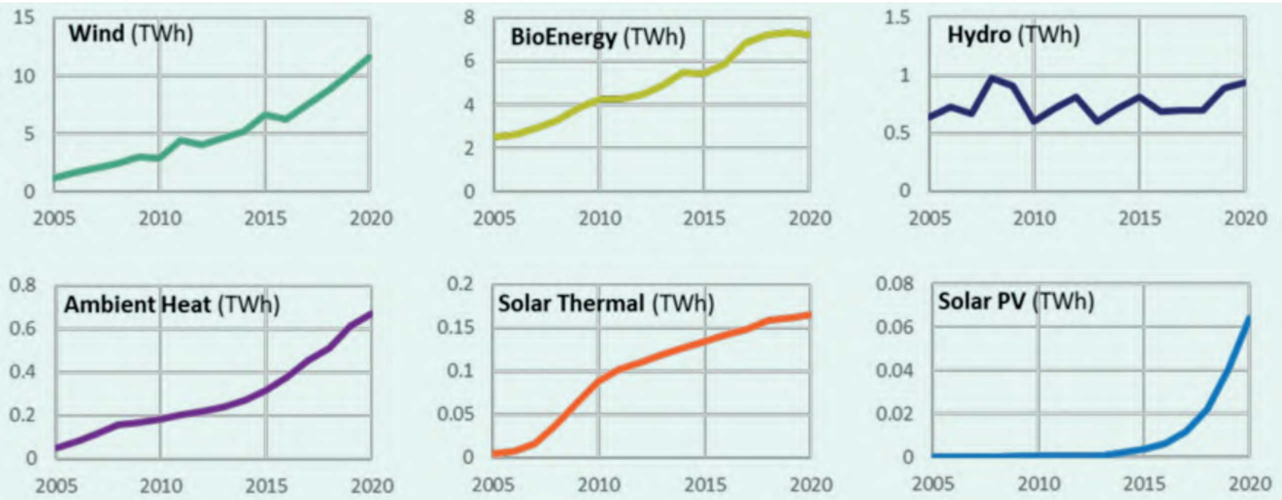


Figure 3.5 Renewable energy trends in Ireland from 2005 to 2020. Source: SEAI (2021f).

Under the EU Effort Sharing Decision, Ireland had a 2020 binding target of 16% for its overall renewable energy share (RES-overall) in its gross final energy, which is the energy used by end consumers plus grid losses and self-consumption of power plants (SEAI, 2021f). This overall target included two national sub-targets: 40% renewable energy share in electricity (RES-E) and 12% renewable energy share in heating and cooling (RES-H). In addition, Ireland also had a binding European target of 10% renewable energy share in transport (RES-T) (Figure 3.6).

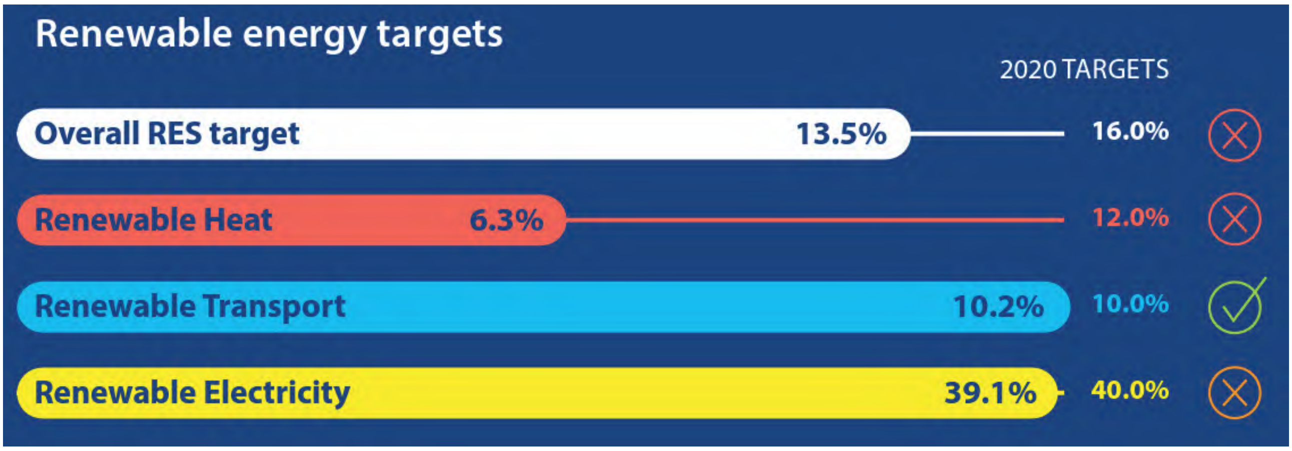


Figure 3.6 Ireland's 2020 renewable energy targets. Source: SEAI (2021c).

In 2020, Ireland reached an overall share of 13.5% renewable energy, which is below its RES-overall target of 16% (SEAI, 2021c). This means that a large portion (86%) of Ireland's energy is still fossil fuel based. Ireland successfully met its target for transport and was very close to meeting its target for electricity, but heating was far from achieving its goal. The RES-T share was 10.2%, versus its 10% target, mainly thanks to biofuel blending (section 4.5.3). The RES-E share was almost on target at 39.1%, versus its 40% target, primarily due to the large growth in onshore wind over the previous decade. The national RES-H share was half its target of 12%, at just 6.3%. With a move to heat pumps and district heating (which can use large heat pumps or other renewables for heat generation/input), heating may be helped by our success with renewable electricity. However, as has been demonstrated by the poor performance to date, the move will be challenging (section 4.4.2).

3.4.1 Renewable electricity

By far the largest source of renewable electricity in Ireland is wind power. It has undergone significant growth over the last 15 years. In 2005, there was 493MW of installed wind capacity (IRENA, 2013). At almost 10 times that figure, Ireland had a total installed wind capacity of 4.3GW at the end of 2020 (SEAI, 2021f). Wind energy generation has almost doubled in the last 4 years, increasing from 6.2TWh in 2016 to 11.6TWh in 2020 (SEAI, 2021f). While the installed capacity of onshore wind has steadily increased, so too has our electricity demand (section 4.3), and the wind resource varies year on year. 2020 was a particularly 'windy' year, which meant that wind energy provided 36.3% of our electricity (Wind Energy Ireland, 2021). In 2021, almost 40% of our electricity came from renewables, 34.8% of which was from wind (Figures 3.7 and 3.8).

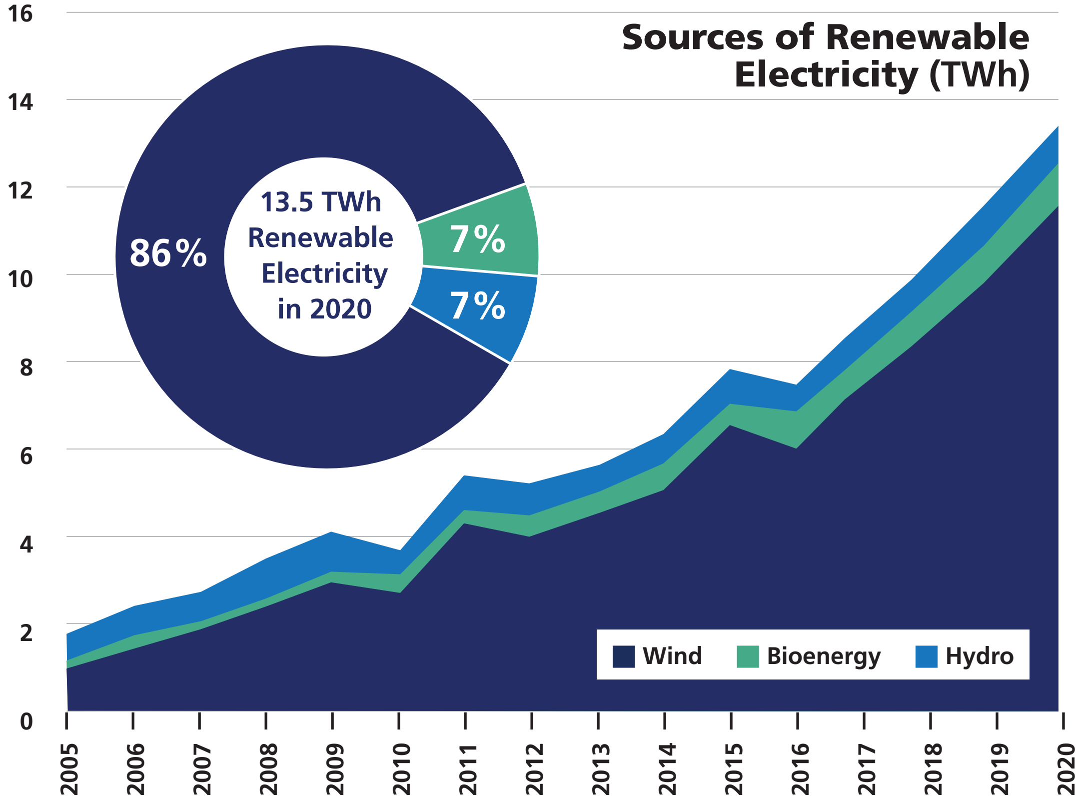


Figure 3.7 Sources of renewable electricity In Ireland between 2005 and 2020. Source: SEAI (2021f)

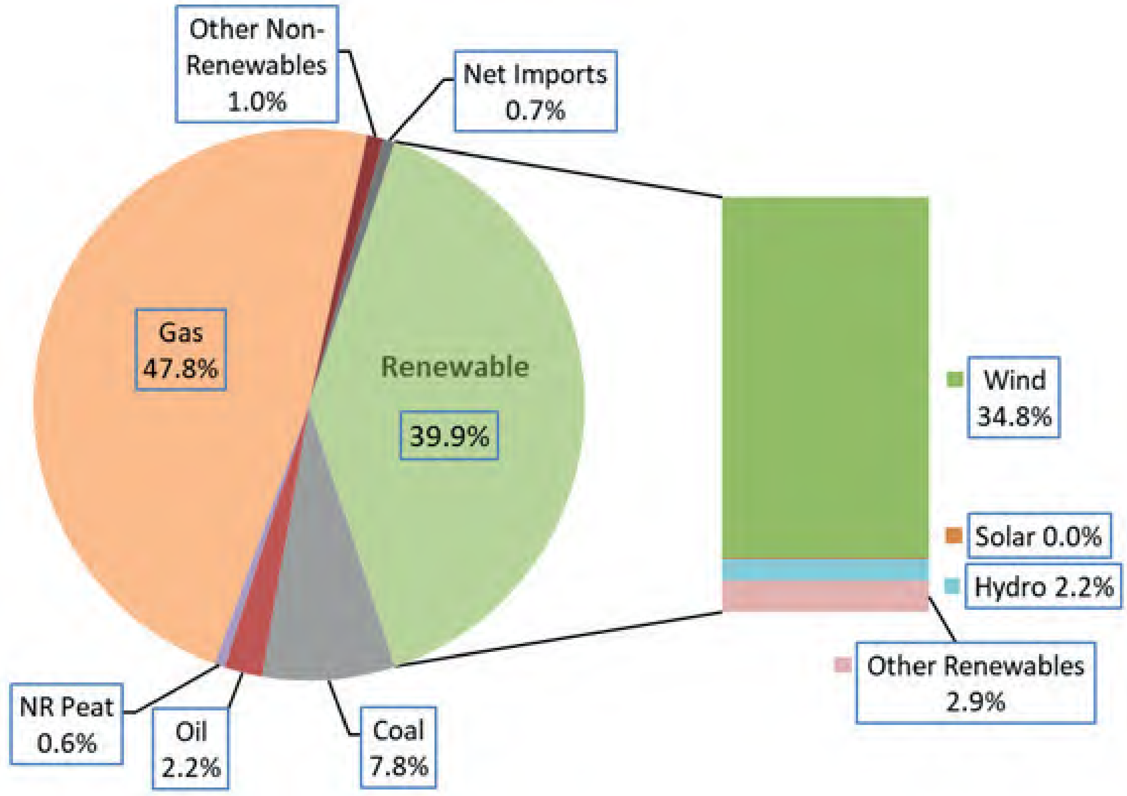


Figure 3.8 The fuel mix in Ireland's electricity 2022. NR, non-renewable. Source: EirGrid (2023).

3.4.2 Renewable transport

Ireland achieved its 2020 RES-T target of 10%. Virtually all of the renewable energy used for transport is in the form of biofuels that are blended with regular fossil petrol and diesel. Under the Biofuels Obligation Scheme, oil suppliers are required to ensure that a portion of the motor fuel (petrol or diesel) that they place on the market in Ireland is produced from renewable sources, e.g. bioethanol and biodiesel (Nora, 2022). The obligation was increased on 1 January 2022 from 12.359% to 14.942% (by volume). Biodiesel was by far the largest renewable fuel type in 2020, providing 88% of the total transport renewable energy, followed by biogasoline (or bioethanol), which accounted for another 11% (Figure 3.9). The success in meeting the renewable energy target for transport was mainly due to the Biofuels Obligation Scheme – not a shift in travel patterns to use sustainable transport modes or reduce car use, i.e. behaviour patterns still need to change significantly (section 5.1.1).

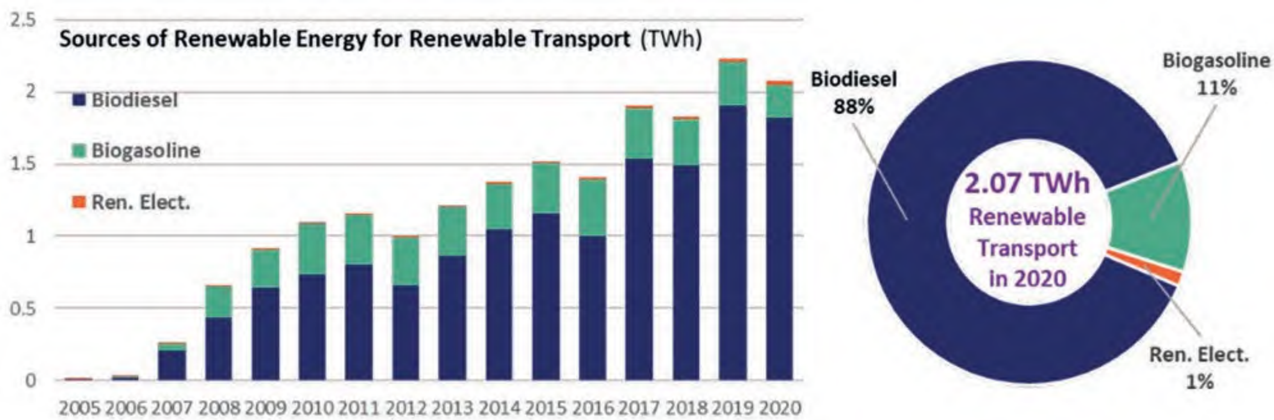


Figure 3.9 Sources of renewable energy in transport in Ireland 2005–2020. Source: SEAI (2021f).

The RES-T result is calculated using a methodology from the EU Renewable Energy Directive. Numerical weightings are applied to certain energy sources to help incentivise the transition to sustainable and renewable transport. While renewable electricity for transport remains low in absolute terms, the last 5 years has seen it rise rapidly, especially through use in private cars. The increase is due to the combination of two factors: (1) increased numbers of EVs on the road and (2) increased electricity generation from renewable sources to power both EVs and electric rail services. Since the RES-T methodology applies a factor of 5× weighting to renewable electricity used in EVs, their contribution to Ireland's binding EU RES-T target of 10% is significantly boosted.

3.4.3 Renewable heat

Ireland is the weakest performing country in the EU in terms of its share of renewable energy in heating and cooling. Heating is still dominated by fossil fuels, at 93% of heat demand in 2021 (SEAI, 2022c). In 2020, Ireland's renewable energy in heating and cooling was mainly solid biomass (58%), with most of this occurring in the industry sector. The second largest contributor to renewable heating is the capture and use of ambient heat energy (19%), using ground or air source heat pumps and related technology. Captured energy from ambient heat sources (0.67TWh) has doubled in the last 5 years, as the roll-out of heat pump technology in both residential and commercial properties has increased (SEAI, 2020c) (Figure 3.10).

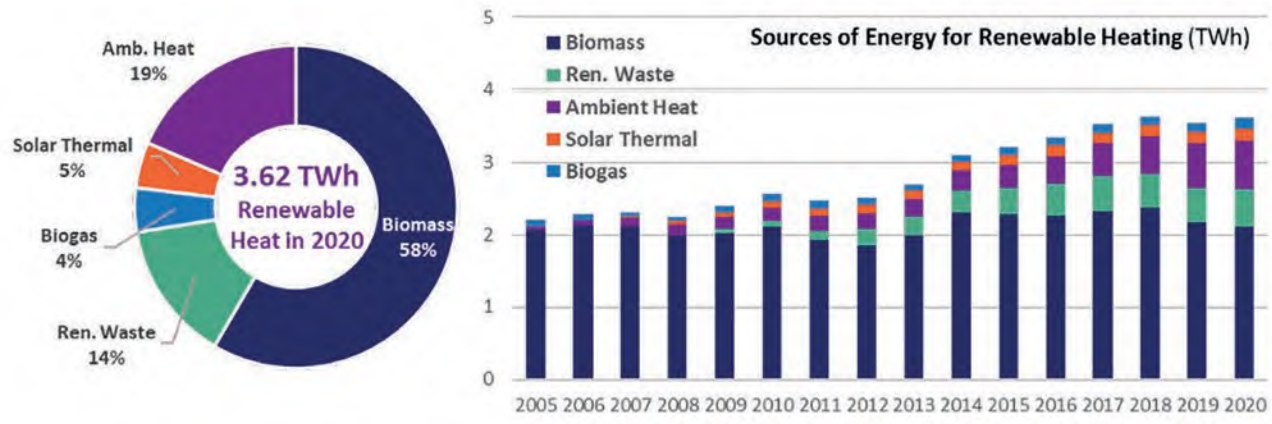


Figure 3.10 Sources of renewable energy in heat in Ireland 2005–2020. Source: SEAI (2021f).

Industry is by far the largest sectoral consumer of renewable energy for heating in Ireland. In total, industry accounts for 61% of renewable heat consumption. The wood and wood products sub-sector alone uses 34% of our renewable heat energy, where wood wastes produced as by-products are used to provide the heat needed for the manufacturing process. The residential sector accounts for over one-quarter (26%) of renewable heating consumption. This share has doubled in less than 10 years, albeit from a very low initial level, with about half of this energy coming from heat pumps.

3.5 Energy security

3.5.1 What is energy security?

Energy security is complex because it comprises many diverse elements. The extensive literature has yet to converge on a unified definition of energy security and there are many different indices available to measure it (Narula and Reddy, 2015; Gasser, 2020). Glynn et al. (2017) identify three key metrics for Ireland:

1. The Supply/Demand Index measures how well a country's energy supply can meet demand.
2. The Herfindahl–Hirschman Index is a measurement of market competitiveness, determined by the market share of energy suppliers.
3. The Shannon–Wiener Index of Economic Diversity measures the share of a particular fuel in the energy mix.

At its simplest interpretation, energy security means having uninterrupted access to a reliable, affordable supply of energy. As introduced in section 3.1, the highly interconnected nature of energy within our society means that this is essential for the maintenance of our economy and comfortable living conditions. Energy import dependency is one of the simplest and most widely used indicators of a country's energy security, with indigenous energy sources generally considered to be more secure than imported energy. There are also intricate interactions with the other two important pillars of energy policy: sustainability and competitiveness.

It is important to consider energy security in the context of the global energy system's significant contribution to climate disruption and the need to align the energy sector with the Paris Agreement (SEAI, 2020c). Focusing on the short-term affordability of energy, energy security is often used to justify fossil fuels and their associated infrastructure with regard to key climate goals (outlined in sections 1.1.2 and 2.1) (Toke and Vezirgiannidou, 2013). For example, in the USA, energy security has been given priority over climate objectives, with the significant expansion of oil and gas extraction through fracking (Nyman, 2018). However, studies of Ireland's future energy system have shown that increased climate mitigation ambition can also result in the co-benefit of improved energy security (Glynn et al., 2017, 2019). For example, both building energy improvements and indigenous renewable energy supply can strengthen energy security, while at the same time reducing our contribution to climate change and bill for imported fossil fuels (SEAI, 2020c).

3.5.2 Ireland's energy security

In Ireland, two indicators highlighted by SEAI are the level of import dependency and the Supply/Demand Index (SEAI, 2020c). The Supply/Demand Index shows an overall increase in energy security over the period 2005–2018. Ireland's import dependency was 67% in 2018, down from an average of 89% between 2001 and 2015. This improvement was mostly due to the beginning of production of gas from the Corrib field and significant growth in onshore wind energy. Despite this improvement, Ireland is still one of the most import-dependent countries in the EU. Oil made up by far the largest share of energy imports in 2018: oil accounted for 73% of total energy imports, natural gas 17%, coal 8.2% and renewables 1.4% (SEAI, 2020c). It is hard to determine exactly where Ireland's imported oil and gas originated.

As introduced in section 3.3.1, in the case of oil, the majority (60–70%) is imported as a refined product (diesel, petrol, etc.) that has already been processed in another country from a range of crude oil sources. In 2018, the UK provided 16% of Ireland's crude oil imports and 69% of its refined product. As illustrated in Figure 3.11, there are many different source countries for each of the oil products.

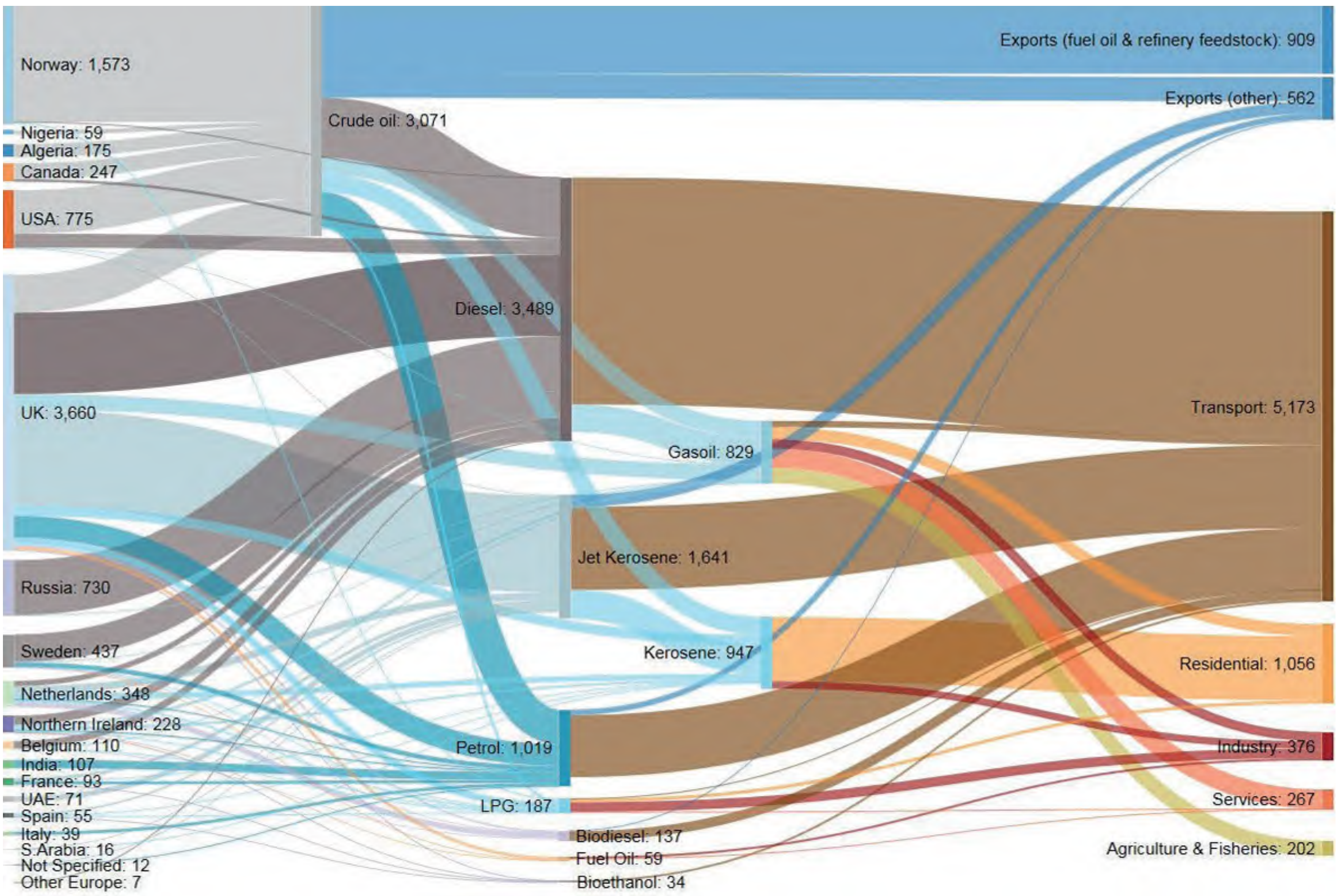


Figure 3.11 Oil and oil product sources in Ireland in 2018. Source: SEAI (2020c).

As noted in section 3.3.3, the output from the Corrib gas field has been in decline, leaving Ireland increasingly dependent on the import of natural gas from the UK through the Moffat entry point. With the continued depletion of production from Corrib, Gas Networks Ireland forecasts that, by 2030, 90% of our gas will come through the Moffat entry point (Gas Networks Ireland, 2022a). Around half of the UK's gas comes from indigenous supply in the North Sea (UK Office for National Statistics, 2022). The majority (60–75%) of the UK's gas imports come from pipelines from Norway, Belgium and the Netherlands. The remainder is in the form of liquefied natural gas from Qatar, Russia, USA and others. The exact amounts from each country have fluctuated a lot over the last 5 years (Figures 3.11 and 3.12).

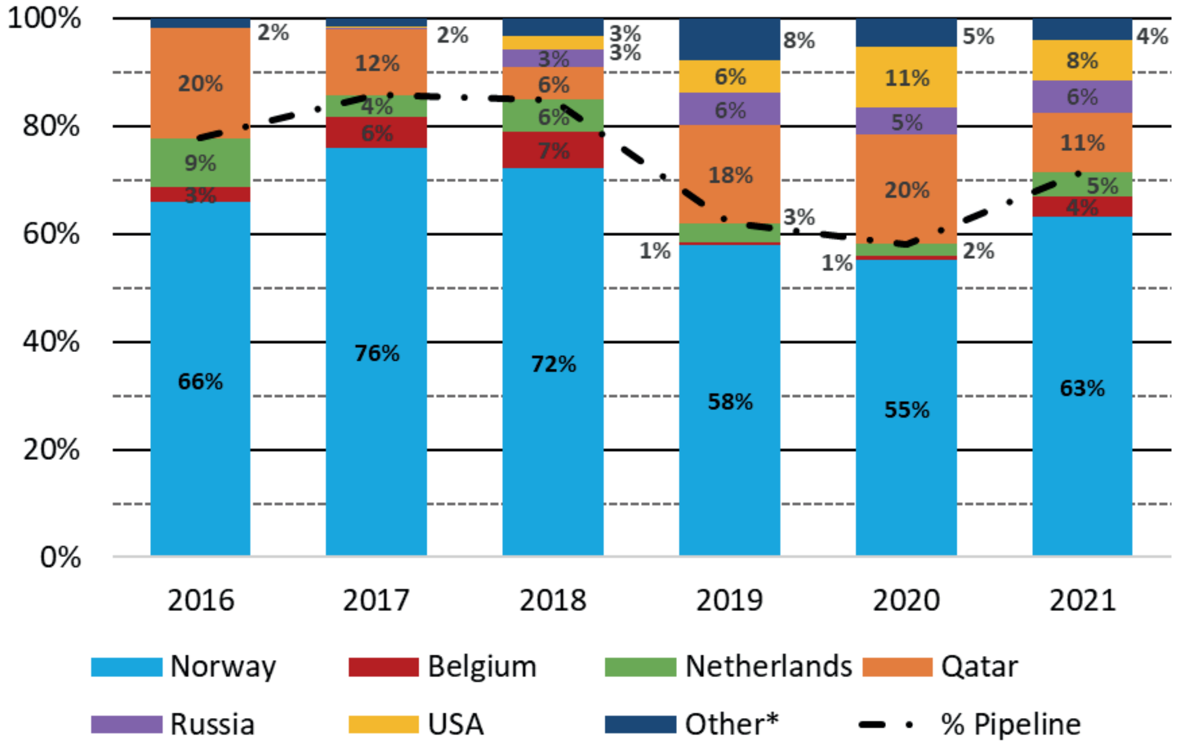


Figure 3.12 Sources of UK gas imports from 2016 to 2021; based on UK Department for Business Energy & Industrial Strategy (2022). *Varies by year, but some common sources are Algeria, Trinidad and Tobago, and Nigeria.

Even before Russia's invasion of Ukraine (section 3.5.3), there were concerns over the security of Ireland's electricity supply. Potential supply shortages have been repeatedly flagged by energy experts (House of Oireachtas, 2018, 2019), and by our electricity system operator. Since 2017, EirGrid's annually released planning statements have consistently highlighted vulnerabilities in our grid due to tight supply–demand margins, and an urgent need to upgrade key elements of our electricity generation and transmission infrastructure (EirGrid plc, 2018, 2021a). On the supply side, we have been slow to build sufficient natural gas capacity, while, on the demand side, electricity demand is rising, primarily due to data centres. In EirGrid's 2022 capacity statement, it highlights that 631MW of previously awarded capacity has been terminated, which means that most of the new capacity expected to come online over the coming years will not be available (EirGrid, 2022). This shortage in supply has raised concerns over grid stability (Commission for Regulation of Utilities, 2022).

3.5.3 Impact of the war in Ukraine

In 2020, the EU imported c.24% of its total energy needs from Russia – 41% of its natural gas needs, 37% of its oil (including crude oil and oil products) needs and 19% of its coal needs (Eurostat, 2022b). However, Ireland has one of the lowest levels of import dependency directly from Russia. In 2020, Ireland imported around 3% of its energy needs directly from Russia (Government of Ireland, 2022a). Within that overall figure, the dependence on Russia for specific fuels, such as diesel, is more significant (Figure 3.13). While Ireland imports limited levels of oil directly from Russia, some of Ireland's imports of oil products may have originated in Russia prior to being refined. Similarly, with gas, Ireland does not import it directly from Russia. However, the interconnected nature of the EU's gas market means that while the UK (Ireland's source of gas) gets a very small share of its gas from Russia (Figure 3.13), the prices are still heavily influenced by Russian supply into the EU's gas network. Due to the large share of our electricity that comes from gas generation (51% in 2020, section 3.3.3), gas prices have a significant impact on our electricity prices (Figure 3.13).

Figure 3.13 Monthly wholesale electricity prices (Ireland) and natural gas (UK) 2019–2022. NBP, natural balancing point.

Regardless of country of origin, the price of oil products in Ireland will be determined by global oil prices. Moreover, since so much of what we buy is made and transported with oil, the price of goods and services have also been significantly impacted. In July 2022, energy prices across the EU were, on average, up by 40% (Eurostat, 2022a). The estimate for economy-wide annual inflation in the EU was 9.8% in July 2022, up from 9.6% in June 2022. Ireland is similar to the European average at an annual inflation rate of 9.6% in July 2022 (Eurostat, 2020a). This is driving a 'cost of living' crisis as household budgets feel the pinch.

4

Future Energy Choices by Technology

Key messages

Ireland has significant potential for renewable electricity. Offshore and onshore wind energy are expected to play a large part in Ireland's future energy system. The combined potential is estimated at 41–55GW installed capacity. For solar photovoltaics (PV), a study commissioned by the Irish Solar Energy Association estimated that putting six solar PV panels on the roof of suitable homes could provide 1.8TWh, equivalent to 22% of all residential demand.

Bioenergy offers a range of alternative liquid, gas or solid fuels that will be needed for areas not suited to electrification, such as heavy transport and industry, and as a means of balancing variable renewable electricity technologies. However, production must be carefully managed to ensure adequate reduction in greenhouse gas emissions and avoid other environmental impacts.

District heating is a promising option for cities and towns where there is densely populated housing near to sources of waste heat, such as data centres or industry. It is estimated that there is enough heat currently going to waste from electricity production and large industries to meet all of Dublin's current heating demand. However, there will need to be clear policy and regulatory support to deliver on this potential.

Hydrogen has attracted a lot of attention, but its exact role in Ireland's energy future is still uncertain. Research shows that green hydrogen can play an important role in electricity generation back-up, heavy transport and some industry where electrification is not suitable.

Geothermal energy has received little attention to date. Research has shown opportunities for both small- and large-scale developments, but the proposed Bill from 2010 has yet to be enacted.

Elements of carbon capture, storage and removal are likely to be needed to meet emission reduction targets.

The widespread uptake of heat pumps and electric vehicles will mean that the electricity grid is the backbone of the future energy system. Maintaining a steady supply will require a diverse generation mix, increased demand flexibility, new forms of storage and more interconnection.

Government support programmes worldwide have kick-started a dramatic decrease in the cost of renewable energy technologies (IEA, 2021c). From 2010 to 2019, there were sustained decreases in the unit costs of solar energy (85%), wind energy (55%) and lithium-ion batteries (85%) (IPCC, 2022c). As highlighted by the IPCC, the energy system transition is already under way, and dramatic improvements over the last decade mean that "Electricity from PV and wind is now cheaper than electricity from fossil sources in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-scale battery storage on electricity grids is increasingly viable" (IPCC, 2022b, p. 89).

Much of Ireland's focus to date has been on the production of renewable electricity (section 3.4.1). Moving forward, deep decarbonisation in heating and transport will require a range of additional technologies. This chapter will provide an overview of the various technology choices, highlighting areas of great potential for Ireland, current status and key elements of deployment. Explanation of the terms used throughout (e.g. levelised cost of electricity or capacity factor) can be found in Annexes A.1 and A.2.

4.1 Wind energy

Ireland has a fantastic wind resource. In 2011, SEAI estimated that Ireland had the potential for between 11 and 16GW of onshore wind and 30GW of offshore wind by 2050 (Figure 4.1). In 2014, the Offshore Renewable Energy Development Plan determined the offshore wind farm development potential to be slightly higher at between 34.8 and 39GW without significant adverse effects on the environment (Department of Communications, Energy & Natural Resources, 2014).

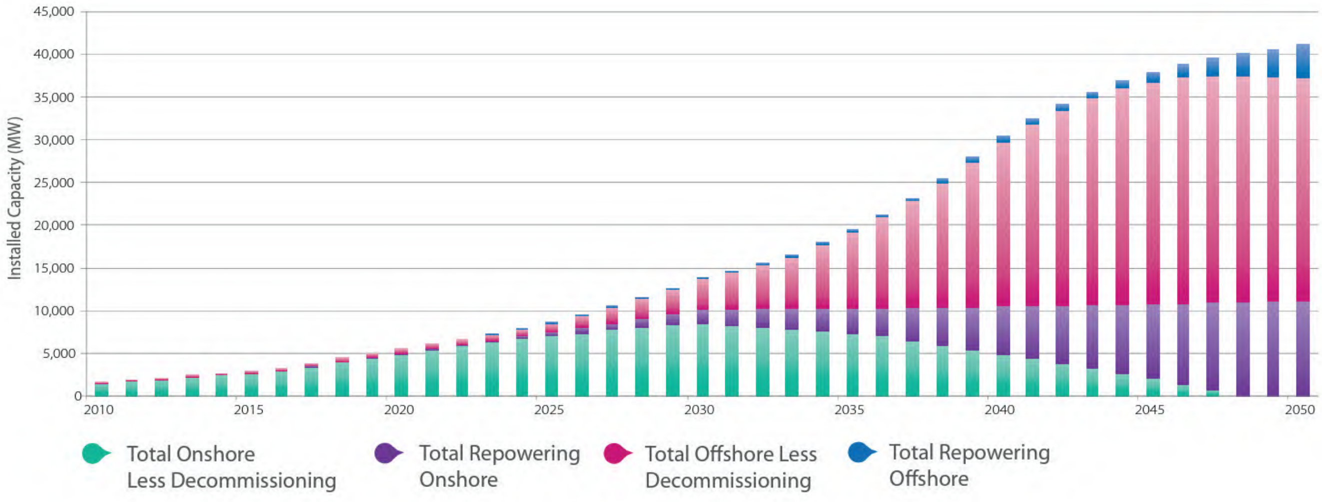


Figure 4.1 Cumulative capacity with repowering of onshore and offshore wind energy. Source: SEAI (2011b).

As wind energy penetration levels rise, the accuracy of the short-term wind forecast (onshore and offshore) will be an important part of the power grid's resiliency (Sweeney, 2020; Sweeney et al., 2020). In addition, thinking longer term, it will be important to understand the potential impact climate change may have on wind patterns (Watson, 2019; Russo et al., 2022). Martinez and Iglesias (2021) found that in the EU there may be a reduction of c.15% in wind power density by 2100 in the worst-case scenario. Demonstrating the regional variability of this impact, Hdidouan and Staffell (2017) in an assessment of the UK found that climate change could increase costs in the south but reduce them in the north.

4.1.1 Onshore wind

With an installed capacity of 4.3GW, onshore wind was Ireland's largest source of renewable electricity in 2020, providing 36% of the total electricity demand (Wind Energy Ireland, 2021). The majority of CO_2 emissions savings achieved in 2020 (4.5 out of 6.5MtCO_2) are thanks to onshore wind energy (SEAI, 2021f). An additional 2.7GW is expected to be installed in the next few years. Increased blade diameter and hub heights have dramatically increased the output per wind turbine over the last decade, which has helped to reduce costs. However, the reduction in installation costs seen in Ireland has not been as substantial as in other EU countries (Duffy et al., 2020a).

The massive expansion of wind energy has not been without its challenges. From a technical perspective, there is a limit to the amount of non-synchronous penetration the grid can handle and other issues associated with the variability of the resource (further detailed in section 4.3). Looking at public attitudes to wind energy in Ireland, poor engagement practices to date have caused a lot of tension (Van Rensburg et al., 2015; Brennan and Van Rensburg, 2016; Brennan et al., 2017; Lennon and Scott, 2017) (further elaborated in section 8.3.1). To continue onshore wind energy expansion it will be critical to improve these practices (Boyle et al., 2022) and have better-informed spatial strategies (González et al., 2016). Another way forward is community benefit schemes to ensure local value from projects and to overcome perceptions of injustice (Brennan and Van Rensburg, 2020) (see section 8.3.4 and Volume 4).

Some studies have suggested looking at smaller or micro-scale wind generation, which could be mounted on buildings (Li et al., 2012; Sunderland et al., 2013). These show limited viability in urban environments, but there is potential for small-scale pole-mounted installations in rural areas (Tummala et al., 2016).

4.1.2 Offshore wind

As an island on the western periphery of Europe, Ireland is well positioned to take advantage of its large sea territories and significant offshore wind resources. Ireland's wind energy resources are among the greatest in Europe (European Environment Agency, 2009), and offshore wind power will play a significant role in its zero-carbon electricity system (Baringa, 2021). Ireland clearly has a unique position with offshore wind, including an opportunity to become an early leader in the emerging floating wind energy market. Despite this, and long-standing developments in planning, there has been relatively little deployment to date, with unresolved issues including grid connection, licensing, and the renewable energy feed-in tariff or equivalent market framework (Joshi et al., 2018; Lange et al., 2018a). Only 25MW of offshore wind energy has been operational in Ireland since 2003. Arklow Bank, which was the world's first wind farm, with turbines over 3MW each, is the only offshore wind farm to be developed in Ireland to date. However, in November 2022, the terms and conditions for the first offshore wind renewable electricity support scheme (RESS) were released (Department of the Environment, Climate and Communications, 2022c). It expects to secure up to 2.5GW of new offshore wind capacity.

Ireland's offshore marine territory is quite expansive and offers huge potential for renewable developments. There has been a growing focus on marine development nationally, with the adoption of the National Marine Planning Framework (Department of Housing, Local Government and Heritage, 2021) and the Maritime Area Planning Act 2021 (Government of Ireland, 2021). The Maritime Area Planning Act 2021 will see the establishment of a new state agency, to be known as the Maritime Area Regulatory Authority, which will be responsible for regulating development and activity in Ireland's maritime area. These decisions will be informed by Ireland's marine spatial plan, called the National Marine Planning Framework.

Irish literature highlights that critical to the success of offshore deployment will be marine spatial planning to manage the impact on the marine environment (Fiduccia et al., 2016; Bates, 2017; Ehler, 2017) and properly engage with coastal communities (Trevisanut, 2014; Soma and Haggett, 2015; Boucquey et al., 2016; Reilly et al., 2016; Farrell et al., 2017; Yates, 2017; Zhang et al., 2017). Lange et al. (2018a) highlight that offshore developments can often lead to conflict, and that, at present, the governance systems (policy, regulation, industry development and public engagement) are disconnected. However, if carefully coordinated, offshore wind presents a great opportunity for Ireland. Kandrot et al. (2020) suggest that by 2030 2.5–4.5GW of domestic offshore wind development could create between 11,424 and 20,563 supply chain jobs and generate between €763 million and €1.4 billion in gross value added (Figure 4.2).

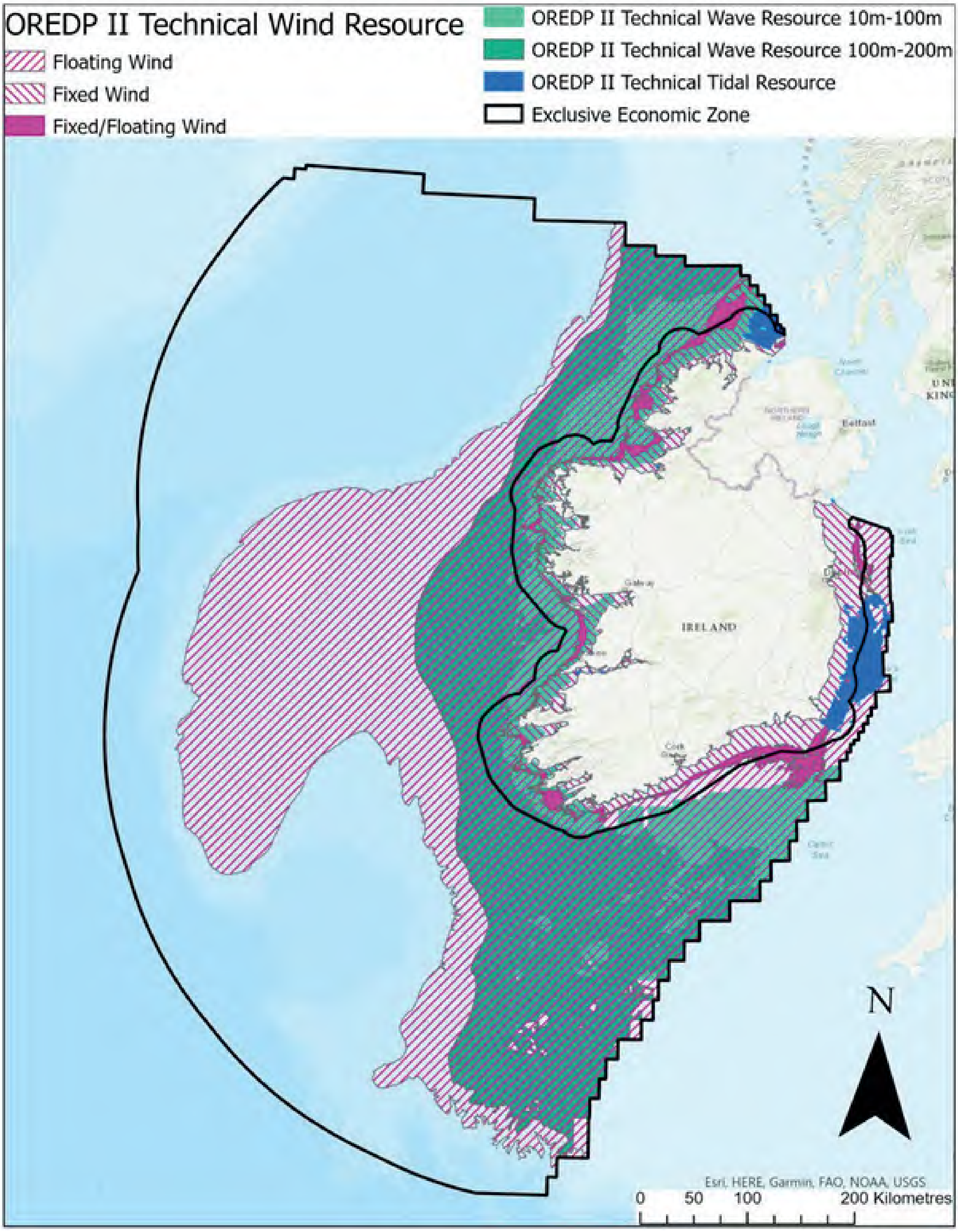


Figure 4.2 Offshore Renewable Energy Development Plan (OREDP) II preliminary study area. Source: ClearLead Consulting Limited (2022).

4.2 Solar photovoltaics

There has been a significant growth in interest in solar PV in recent years for both commercial-scale and rooftop installations. This is due to the substantial reduction in costs and improvements in the technology over the last decade. Globally, according to the IEA's World Energy Outlook 2020, solar PV is now the cheapest source of electricity in history (Cozzi et al., 2020).

The first instalment of the new RESS in 2020 had 63 successful solar projects with a proposed capacity of 796.3MW, providing 767GWh, which is equivalent to the annual electricity demand of 153,000 homes. The proposed solar farms are primarily located along the south-east coast due to the availability of sunlight there. The first commercial solar farm was connected to the grid in April 2022 (Department of the Environment, Climate and Communications, 2022c). As noted in section 3.5.2, there are now enough projects in the pipeline to exceed the previous Climate Action Plan 2021 target of 1.5–2.5GW solar power generation by 2030.

Interest has also been growing for rooftop solar PV on households, farm sheds, public buildings and businesses. A study commissioned by the Irish Solar Energy Association estimated that there are 1.3 million homes with a roof suitable for a solar PV system, which could provide 3.1TWh, equivalent to 36% of all residential demand (Joshi and Deane, 2022). Systems under 50kW capacity are eligible for the micro-generation support scheme (Department of the Environment, Climate and Communications, 2022b), and new planning permission exemptions have been added for rooftop installations (Department of Housing, Local Government and Heritage, 2022). Previously, installations on homes over 12m2 or that were 50% of the roof area had to apply for planning permission. However, for larger installations (between 50 and 1,000kW), which may be appropriate for farms or businesses, there is currently a lack of guidance and support (Ricardo Group, 2022).

4.3 Ireland's future electricity grid

Studies have shown that, as Ireland changes from importing fossil fuels to independently producing clean energy, electrification has increased to best utilise the renewable energy (Glynn et al., 2019; Yue et al., 2020b). Ireland's targets for battery electric vehicles (BEVs) and heat pumps complement its renewable electricity ambitions (section 4.4): the electrification of transport and heat is key to the decarbonisation of the energy system (IEA, 2021b). Similar trends are predicted worldwide and, by 2050, electricity is set to be the main energy carrier, accounting for more than 50% (direct) of final energy demand – a significant increase on the current figure of 21% (Reuters, 2021). Within this, the make-up of our electricity grid is also shifting, as houses, business and other buildings become generators as well as consumers. EirGrid's 'Shaping Our Electricity Future Roadmap' included an expectation for 500MW of microgeneration in Ireland by 2030 (EirGrid plc, 2021b), which would represent a significant switch away from what to date have been primarily large-scale developments.

4.3.1 Challenges over the next decade

A key challenge facing Ireland's grid over the next decade is that, while we are trying to integrate increasing levels of renewables, there is also significant growth in electricity demand. The electricity grid is one of a few examples of an all-island system, shared between Northern Ireland and the Republic of Ireland. The all-island annual electricity demand was 40TWh in 2021 and is expected to increase to between 49 and 62TWh by 2030 (EirGrid and SONI, 2022), which is a significant increase on the previous projections from 2021 (Figure 4.3).

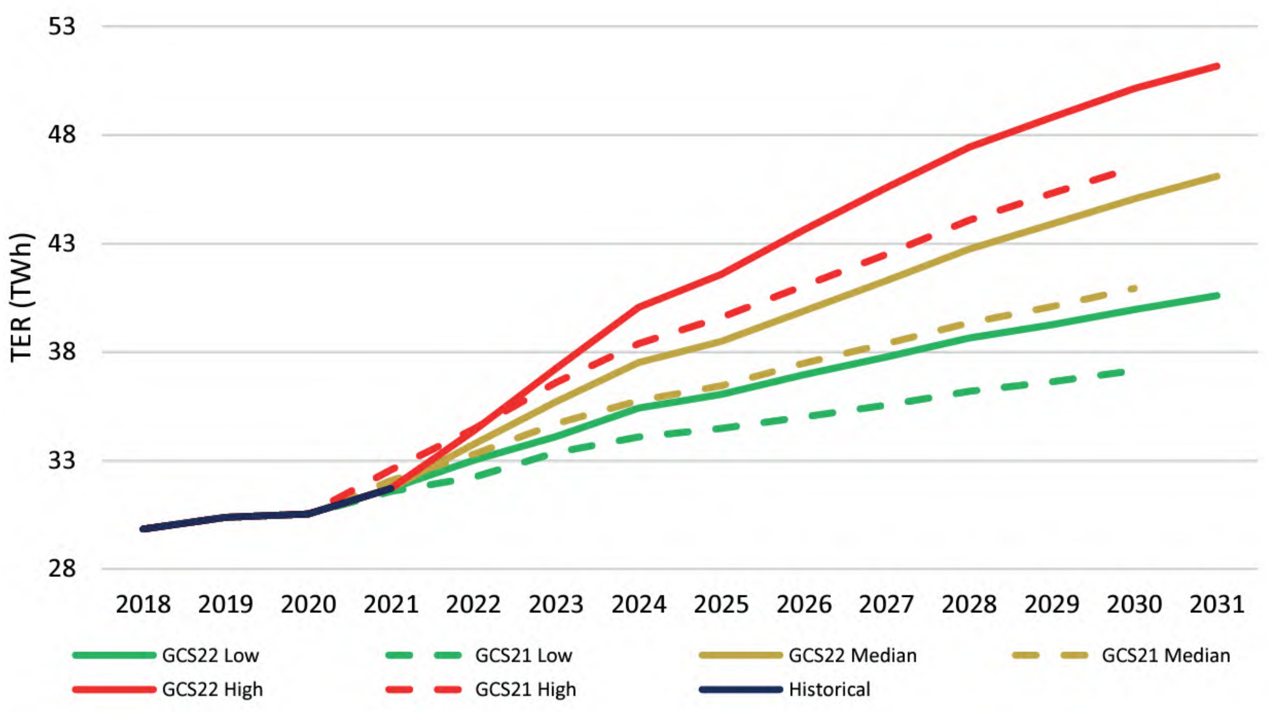


Figure 4.3 Total electricity requirement forecast for Ireland 2021–2031, comparing projected growth in generation capacity statements from 2021 and 2022. Source: EirGrid and SONI (2022).

A small portion of this is the electrification of heating and transport (section 4.4), but it is mainly associated with data centres. This poses a risk to our decarbonisation goals and security of supply (Daly, 2022; Deane et al., 2022). In the median demand scenario, data centres represent over 28% of electricity demand in 2031 (EirGrid and SONI, 2022), which would surpass the electricity demand from all households. With regard to emissions, even if the 80% RES-overall target is achieved, the extra demand associated with data centres may add between 0.6 and 1.3MtCO_2 in 2030 (Deane et al., 2022).

Fossil fuel-powered generators are also being shut down, which makes the task of maintaining grid stability even more challenging. In a study commissioned by Wind Energy Ireland (Baringa and TNEI, 2022), investigating a scenario for 80%

renewable electricity by 2030, it was highlighted that there will be 1.5GW less dispatchable capacity[15] in 2030. There will be a total reduction of around 3.5GW from coal and peat plants being shut down, along with reduced oil generation, but this is partly compensated by a growth of 2GW of new gas capacity. As we increase the levels of renewable generation on the electricity system, the operation of the electricity system will change, with system services, interconnection, demand flexibility and storage (short and long term) playing an increasingly important role. A further technical discussion on grid issues is included in the Annex A.2.2.

4.3.2 The role of interconnection

The EU has set an interconnection target of at least 10% by 2020 (Ireland's level was 7% in 2017) to promote security of supply and encourage countries to connect their installed electricity production capacity to share resources (Mehigan and Deane, 2020). There are already two interconnectors between the island of Ireland and the UK, one in Ireland and one in Northern Ireland. An additional two interconnector projects are at a preliminary stage: the Greenlink Interconnector between Ireland and the UK and the Celtic Interconnector, which is the first planned interconnector between Ireland and France (Table 4.1). Ireland's location on the periphery of Europe limits its diversity in terms of interconnection options. This challenge can be addressed to a degree through the introduction of storage technologies and flexibility solutions into the energy system (following section 4.3.3).

Table 4.1 *List of current interconnection projects*

Project	Description	Target commissioning year
Greenlink Interconnector	Project providing interconnection to Great Britain	2024
Celtic Interconnector	Interconnector between Ireland and France	2026
LirIC	Interconnector between Northern Ireland and Scotland	2028
MaresConnect	Interconnector between Ireland and Wales	2027

Source: EirGrid (2022).

4.3.3 Flexibility and storage

Moving to an electricity system based on renewables presents challenges for grid stability and maintaining supply. Providing a stable electricity supply using just renewables would mean that we must store enough energy (wind, solar and wave) to cover periods when their output is reduced (low winds, night-time). Large banks of batteries can technically achieve this and can release electricity when supplies are low. However, this can cover only short periods of a few hours. We must plan for worst-case scenarios, such as several weeks in a row of low wind speeds during a period of high demand, and therefore a mix of technologies is needed for a more resilient solution.

This is intrinsically linked to electrification. Currently, energy tends to be stored and used only when needed. Fossil fuels offer relatively easy storage and distribution and benefit from decades of investment in infrastructure, such as filling stations, gas networks and strategic reserves. They are what we call dispatchable, meaning that they can be easily used or turned on/off when needed, provided that the supply chain continues to work. Gaseous and liquid renewable fuels, such as biomass for heat, biodiesel for transport and biomethane for industry, can offer this same flexibility and be stored/distributed in the same way. However, producing enough bioenergy to cover current energy demand would be beyond what can be sustainably produced (section 4.5). Therefore, these fuels are only part of the solution and perhaps most suited to applications where electrification is not practical, or as a back-up.

Baringa and TNEI (2022) estimate that over 2GW of battery storage will be needed by 2030 to achieve the 80% RES-overall target. However, the largest dispatchable load would be 6 hours. Other options will be needed for longer periods of low wind potential over days or weeks. Within reason, demands such as charging EVs, home or water heating, and some

[15] Generation that can be turned on and off quickly. Gas is by far the most flexible of the dispatchable fossil fuels, able to quickly ramp up and down to accommodate wind. Others are less flexible but provide substantial inertia.

industrial processes may be managed to best line up with times of higher renewable energy output or lower overall system demand, thus reducing the amount of storage required. For example, offering households cheaper off-peak electricity would incentivise charging EVs overnight when other demands are lowest. To minimise the waste of curtailed wind energy, some studies have suggested that heat pumps offer a means of diverting this energy into homes, and in particular that this could target those in energy poverty (Agbonaye et al., 2022).

4.4 Electrification of heat and transport

The success in decarbonising Ireland's electricity system can help the areas that have made significantly less progress to date by moving to technologies such as electric vehicles and heat pumps. These offer clean alternatives to fossil-fuelled home heating and private cars. However, it is widely recognised that it is not possible to electrify all heat and transport requirements, e.g. high-heat processes in industry and freight transport. For these applications, bioenergy will be an important alternative (section 4.5). In addition, Ireland's significant offshore wind potential provides a strong basis for the production of green hydrogen (section 4.8).

Thanks to their greater efficiencies, both heat pumps (Haben, 2020) and BEVs (SEAI, 2021b) are approaching or even surpassing cost parity with their fossil fuel counterparts.

4.4.1 Electric vehicles

The Irish government has very ambitious targets for EVs, with the aim of having 175,000 passenger EVs on Irish roads by 2025 and 845,000 by 2030 (Department of the Environment, Climate and Communications, 2022a). This is expected to result in 30% of the private car fleet being electrified by 2030, with all new car registrations to be electric in subsequent years (ibid.). By the end of June 2021, there were 41,000 EVs (both battery and plug-in hybrid) on Irish roads (Department of Transport, 2021a).

It is important here to draw a distinction between plug-in hybrid electric vehicles (PHEVs) and BEVs. There is no role for PHEVs in the future transport system; all cars will need to be BEVs. Even though PHEVs are advertised as low emitting, they typically emit two to four times more on the road than advertised (Plötz et al., 2020, 2021). The combined weight of a battery and engine means that they perform worse than the fossil fuel alternatives.

BEVs have three key benefits:

1. As the grid decarbonises so too does their energy source.
2. They do not produce exhaust air pollutants.
3. They are much more efficient than internal combustion engines (ICEs). This is because there are many fewer moving parts and the conversion of stored energy in a battery to motion is much more efficient than burning fuel. Typically, more than 85% of the energy in the battery of an EV is used to propel the car forward, and most of the losses are in the form of heat. In an ICE car, the value is closer to 40%. Thus, an ICE car requires more than twice as much energy to cover the same distance.

Research on the uptake of EVs highlights a range of financial and non-financial factors influencing uptake: subsidies, regulatory measures, charging infrastructure development and raising awareness (Coffman et al., 2017; O'Neill et al., 2019; Mukherjee and Ryan, 2020). In Ireland, EVs receive government support through the SEAI grant scheme on purchase, Vehicle Registration Tax (VRT) relief and toll reductions worth up to approximately €15,000 per vehicle (Caulfield et al., 2022). Other policy incentives, including scrappage schemes, interest-free loans, access to bus lanes, speed limit changes, parking incentives or emission-linked congestion charging, are under consideration (Department of Transport, 2021a). The key policy levers identified by Mulholland et al. (2018a), in their assessment of EVs for private travel in Ireland and Denmark, was banning ICEs and VRT subsidies, which they warn comes at a loss to the exchequer in the form of tax foregone.

To overcome range anxiety, international research has shown that the expansion of the charging network (Sierzchula et al., 2014), and in particular fast chargers (Neaimeh et al., 2017), is a critical driver of increased EV market share. However, continuous governmental support for public infrastructure has been insufficient to date, with home charging accounting for 80% of charging sessions (Department of Transport, 2021a) and charging/driving patterns (Weldon et al., 2016).

EVs offer significant benefits over ICE cars, and over 47,000 EVs had been sold in Ireland by end of 2021. However, they are not a perfect solution. While they are an essential means of decarbonising our private car travel, they do not address the more critical issue of reducing our car dependence. In addition, EVs are generally promoted as being zero-emission vehicles. However, this ignores non-exhaust particles (brake, tyre and road wear), which are unregulated in the EU (Kriit et al., 2021). Another consideration is the battery materials. There is quite extensive Irish research on battery development (McNulty et al., 2020; Collins et al., 2021; Imtiaz et al., 2021), fuel cell development (Collins et al., 2021) and battery recycling (Fallah et al., 2021).

4.4.2 Heat pumps

Currently, heating in Ireland relies heavily on fossil fuels, with only 6.3% coming from renewable sources in 2020 (see Figure 3.6). In 2019, there were an estimated 44,000 heat pumps installed in Ireland. Under the Climate Action Plan 2021, the government target is to have 600,000 installed by 2030, of which 400,000 will be in existing buildings. Heat pumps are a fantastic piece of engineering. They can turn 1 unit of electricity into 3.5–4 units of heat. This remarkable efficiency, known as the coefficient of performance, is achieved by cleverly manipulating the thermodynamic laws to draw heat out of the environment (air, water or ground). Most Irish home are likely to have a heat pump already, as this is how a refrigerator works. There are a range of different types of heat pumps, which can be understood in terms of the source of heat and how it is then delivered. For example, an air-to-water system takes energy from the air to provide hot water, while a ground-to-air system would take energy from the ground to provide hot air. The majority of installations in Ireland, taking place in domestic dwellings, are air source heat pumps.

There are a number of studies on heat pumps in Ireland, particularly in residential applications. Gaur et al. (2021) offer a comprehensive review of heat pumps, while Carroll et al. (2020) provide a systematic review of air source heat pumps with a focus on field trials. Kelly et al. (2016) estimate that the health and environmental benefits associated with air pollutant reductions from homes moving to heat pumps instead of fossil fuels could be in the region of €80–125 million per annum. Other Irish research has investigated the gap between operation- and product-rated performance (O'Hegarty et al., 2021, 2022), the impact of heat pumps on power system and electricity demand (Chesser et al., 2020, 2021; Gaur et al., 2022b), heat pumps as a means of storing excess renewable energy (Vorushylo et al., 2018), and public preferences for heat pumps (Meles et al., 2022).

4.5 Bioenergy

Renewable energy that is generated from organic material or plants is called bioenergy. Other carbon sources such as agricultural and food waste, waste vegetable oils and forest residues can be used, as well as resources that can be replenished rapidly, such as grass and purpose-grown crops. The combustion of bioenergy releases CO_2 into the air, but this is offset by the CO_2 consumed by plants during growth or prevented emissions in the case of wastes, making it a zero-carbon renewable resource. This makes it different from fossil fuels, which release CO_2 into the atmosphere that has been stored for millions of years.

Bioenergy technologies are diverse, span a wide range of options and technologies, and can be liquid, solid or gas (Figure 4.4). A biofuel is any liquid fuel derived from biological material, such as agricultural wastes, crops or grass. Biofuels, such as bioethanol and biodiesel, are substitutes for fossil fuels, which when blended with petrol and diesel help dilute the carbon content of widely used transport fuels and reduce emissions. Biomass generally refers to woody crops, which are primarily used in heating, but can also be processed into gaseous or liquid fuels. Finally, biogas, usually in the form of biomethane, is produced by breaking down organic matter such as grass, slurry, seaweed and waste food. Biogas is particularly useful, as it has potential to provide heat, electricity and transport. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonisation of energy.

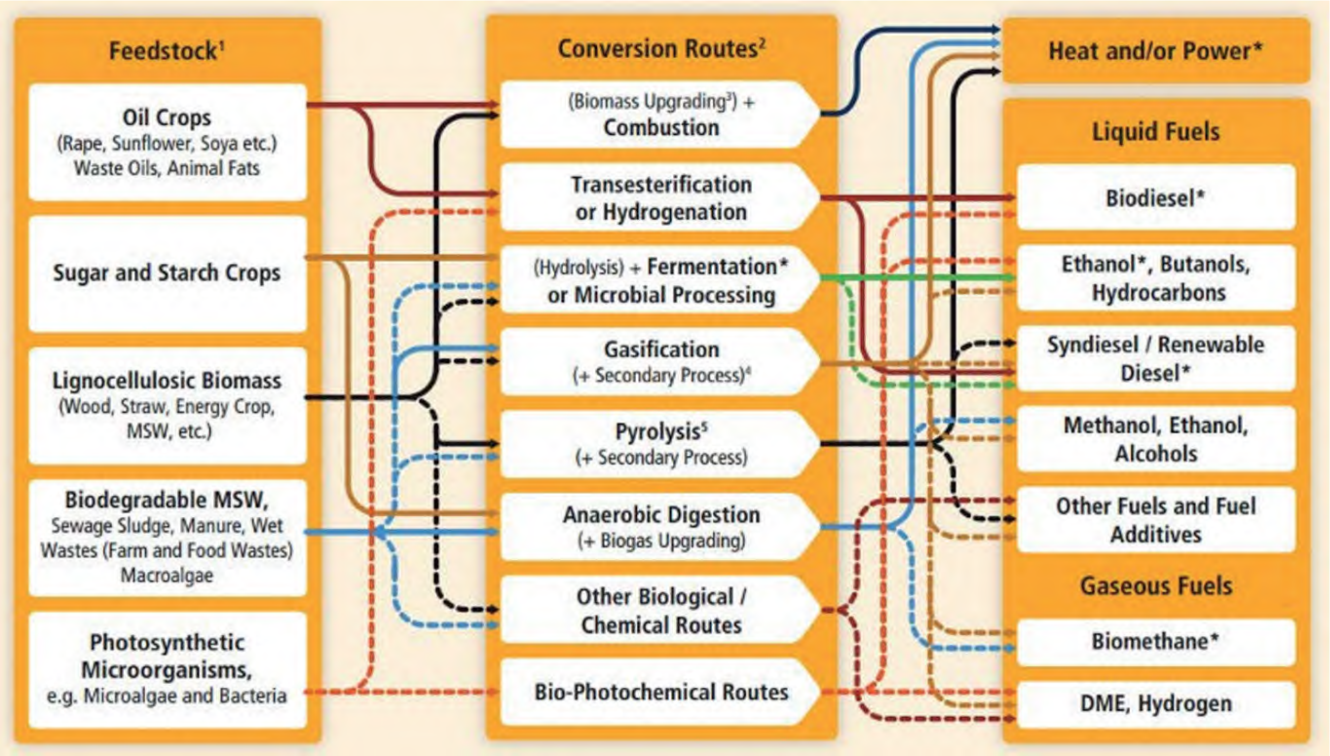


Figure 4.4 Illustration of the varies forms of bioenergy: feedstocks, processes and uses. DME, dimethyl ether; MSW, municipal solid waste. Source: Deane et al. (2021a).

Globally, the growth of dedicated energy crops has raised concerns in terms of both land use competition (i.e. food production) (Hasegawa et al., 2020) and environmental impacts associated with monoculture (Calvin et al., 2021). Within the EU, there is strong governance (acts, regulations and guidelines) that directly and indirectly ensure the sustainability of all types of bioenergy, including consideration of land use and associated agricultural practices. These include the Renewable Energy Directive ((EU) 2018/2001), Directive to reduce indirect land use change for biofuels and bioliquids ((EU) 2015/1513), and Delegated Regulation on Indirect Land-Use Change ((EU) 2019/807). Wesseler and Drabik (2016) highlight that in the EU context the debate about food versus fuel is outdated. The reason for this is that many of the problems identified with food and bioenergy have already been addressed via several EU rules and regulations, including those on water use, fertiliser and pesticide use, protection of habitats and the sustainability of biofuels. However, fuels produced outside the EU are harder to guarantee. The concerns over land use are reflected in the 'Amendment to the Renewable Energy Directive to implement the ambition of the new 2030 climate target', published in July 2021, which sets a limit of 7% for first-generation biofuels in transport.

In the SEAI national heat study, bioenergy provides between 7% and 17% of heat demand by 2030 and a similar proportion in 2050 (SEAI, 2022l). The authors estimate that the total sustainable domestic bioenergy resource (both biogas and energy crops) is between 8 and 13TWh in 2030 and remains about the same until 2050 unless there is significant land use change (SEAI, 2022o). The potential for up to 25TWh worth of wood pellet imports in 2030 or as high as 50TWh by 2050 is also identified. However, this would require upgrades to port infrastructure, and guaranteeing the sustainability of these imports is challenging. The national heat study also stresses that nationally appropriate sustainability governance is required to minimise upstream emissions, align with circular and bioeconomy goals, and avoid increasing emissions in non-energy sectors (SEAI, 2022l). In a similar study focusing on transport and the role of bioenergy, Deane et al. (2021a) propose that bioenergy could provide 20TWh by 2030 and 36TWh by 2050. The three key uses identified were biomass in power generation, biofuels in freight transport and biogas in industry (Figure 4.5). This is in line with most peer-reviewed literature (Chapter 7).

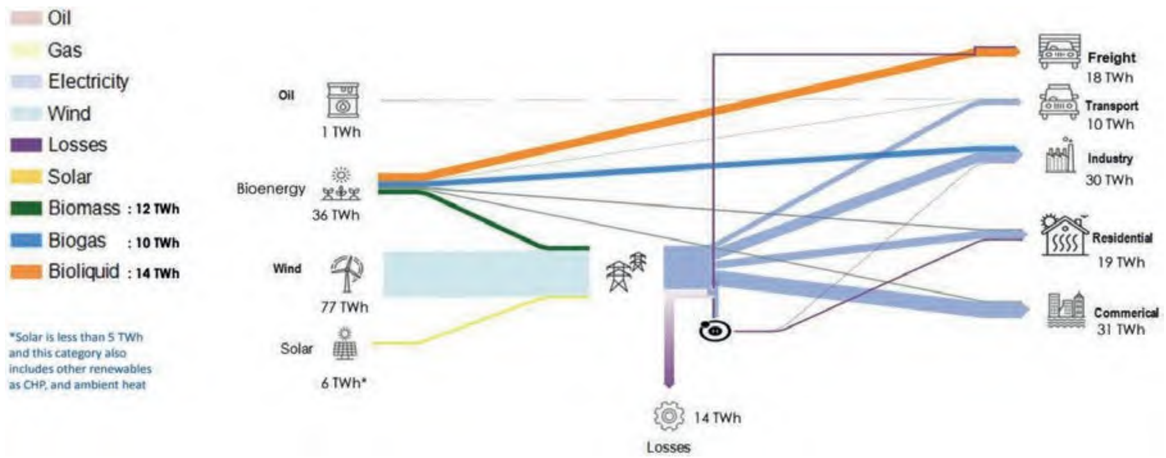


Figure 4.5 The potential role of bioenergy in Ireland's energy system in 2050. Source: Deane et al. (2021a).

A key determinant of bioenergy development will be the amount of land made available for it. The SEAI national heat study identified two scenarios: a stable herd scenario, which has a total area of 67kha for growing perennial energy crops by 2030, and a land use change scenario, which sees a reduction in the national herd and a total area of 103kha for growing energy crops (SEAI, 2022o).

4.5.1 Biomass

Solid biomass is sourced from feedstocks such as forest residues and energy crops. Today, in Ireland, most of our biomass comes from sawdust and off-cuts, which are by-products of the forestry industry. It is primarily used in heating or electricity generation but can also be converted into a gas for use in transport. One use of biomass identified in Ireland was co-firing with peat with the aim of increasing indigenous resource utilisation and fuel security. A key challenge is that transporting the biomass over large distances negates the GHG savings (O'Mahoney et al., 2013). Emission reductions are most effectively achieved through reduction in peat use, as opposed to co-firing. There is likely to be a role for bioenergy in combination with CCS in Ireland's net zero energy system (section 7.2), but, for now, biomass is best used in heating. However, this does present a trade-off with air quality.

Renewable heat energy is dominated by solid biomass use (58% in 2020, see Figure 3.10), particularly in industry, and the majority of this comes from forest residues (Figure 4.6). The current share of biomass resources for energy that is imported is 37% and this is expected to fall to 17% by 2030 (Department of Communications, Climate Action and the Environment, 2020), with the assumption that domestic forestry, agricultural residues and waste resources are harnessed to meet growing demands in heat and transport.

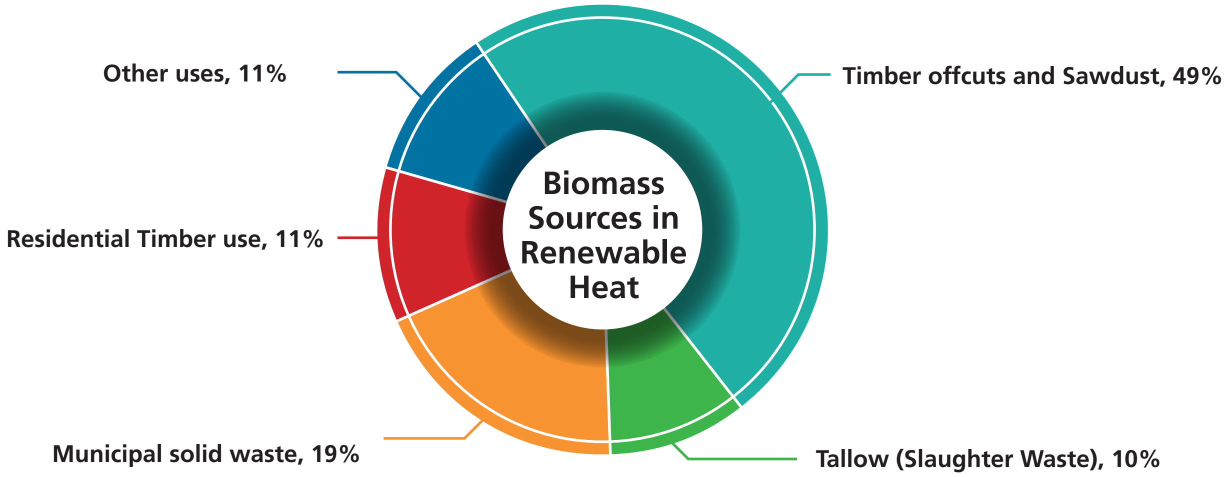


Figure 4.6 Ireland's sources of biomass. Source: SEAI (2021c).

In a report funded by Renewable Energy Ireland, XD Consulting examined scenarios for generating 40% of renewable heat by 2030 (XD Consulting, 2021). The authors outline an indigenous forestry and energy crops resource of 9.7TWh, the majority of which would come from the forestry planting targets in the Climate Action Plan 2019, an average of 8,000ha per annum of new forest, which the Irish Bioenergy Association forecast could provide 6.3TWh per year by 2030. 11% of Ireland is forested, and 31% of harvested wood is used for energy. However, sustainable Irish forest wood is a limited resource, and Fitzpatrick (2016) estimates that steady-state production can only supply only a fraction of demand (3.4TWh[16] in 2028 – highest value).

Energy crops such as short-rotation coppiced willow or miscanthus have significant potential (Caslin et al., 2015a, 2015b). Although willow is harvested only every 4 years, when the quantities harvested are averaged out over this 4-year period, it typically delivers the same yield as miscanthus, which is harvested every year. One hectare of willow wood chip at 20% moisture has the same energy content as 4,500 litres of home heating oil (Caslin et al., 2015b). An SEAI report from 2015 estimated that, in total, 203,000ha could be available for growing willow and miscanthus (SEAI, 2015).

4.5.2 Biogas

Biogas is a mixture of CH_4, CO_2 and small quantities of other gases produced by the breakdown of carbon-rich organic matter in an oxygen-free environment (anaerobic digestion). This biogas is essentially the same as natural gas but is produced from renewable sources and contains some impurities. Biomethane is not inherently good, and there are lots of factors to consider (Grubert, 2020), for instance CH_4 leakage rates have a large influence on life cycle emissions. The composition of biogas depends on the type of feedstock and the production pathway. A wide variety of feedstocks can be used to produce biogas, including specifically grown energy crops such as grass silage or seaweed, animal manure, the organic fraction of municipal solid waste, wastewater sludge and other industry or processing by-products.

It can be combusted in boilers to produce heat, or in combined heat and power plants to provide both heat and electricity. Alternatively, biogas can undergo further upgrading to remove CO_2 and produce almost pure biomethane. This biomethane can then be injected into the gas network to lower the carbon intensity of the gas grid, much in the same way that renewable electricity has done for the electricity grid. The first renewable gas injection facility in Ireland was commissioned in 2019 and was declared a gas entry point in May 2020 (Gas Networks Ireland, 2022a). Biomethane is thus burned in domestic and industrial gas boilers, with no reconfiguration needed. Another option is for it to be used in the transport sector in compressed natural gas vehicles. It could also potentially be used in Ireland's gas-fired power stations.

[16] 12.1PJ; converted using 1PJ = 0.277778TWh.

The biogas industry in Ireland is significantly less developed than in other European countries, as it has been neglected by national policy to date. Some of the key policy elements that are lacking include planning or regulatory guidance, a certificate scheme for renewable gas, a long-term policy roadmap and proper financial supports (Ricardo Energy & Environment, 2017). In contrast, Denmark has had stronger policy support for biogas development over the last decade and it now makes up 15% of Denmark's gas consumption (IEA Bioenergy Technology Collaboration Programme, 2021). In another example, Sweden has made great progress at reducing its transport emissions, thanks largely to the efforts of local municipal governments shifting public bus fleets to biogas produced from residues (Ammenberg et al., 2021).

There has been extensive research into biogas potential in Ireland. Keogh et al. (2022a) provide a comprehensive review of biogas injection into the natural gas grid. There is a range of Irish studies on this issue that look at upstream optimisation, i.e. feedstock types and locations (O'Shea et al., 2016; O'Shea et al., 2017; Singlitico et al., 2018, 2019; Beausang et al., 2020; Deng et al., 2020), and downstream optimisation, i.e. use of the biogas (Mulholland et al., 2016; Keogh et al., 2022a, 2022b; O'Shea et al., 2022b).

The size of anaerobic digestion plant can vary, much in the same way other renewable-generating plants can. O'Shea et al. (2022a) provide a comprehensive review of options for large anaerobic digestion plants that require transport to and from the plant for digestate, feedstock and biogas, while other studies have investigated the potential for smaller on-farm plants to look at the potential uses for the gas in large industry nearby (Céileachair et al., 2021) and the impact that seasonal slurry availability would have on biogas production (Céileachair et al., 2022). Other novel plant configurations, such as distributed anaerobic digestion plants that pipe the biogas to a nearby large user, have also been explored (O'Shea et al., 2017).

The production of sustainable biomethane can help the agricultural sector reduce its emissions. Most of the GHG savings associated with the process come from reducing the amount of CH_4 emitted to the atmosphere through slurry storage (Figure 4.7). However, considering that biogas is itself CH_4, it is thus crucial that CH_4 emission leakage is monitored. Beausang et al. (2021), assessing different mixes of slurry and grass silage digestion, highlight that the GHG emissions saving potential is highest with high proportions of slurry and low proportions of grass. They found that high shares (80%) of grass silage resulted in net positive global warming potential due to the emissions incurred from using fertiliser to provide additional grass silage for this mix. A by-product of producing biomethane through anaerobic digestion is digestate, which can be used to replace chemical fertilisers or slurry spreading. An important co-benefit is that digestate has a lower environmental impact than traditional slurry spreading, without impacting grass yield (Nolan et al., 2020).

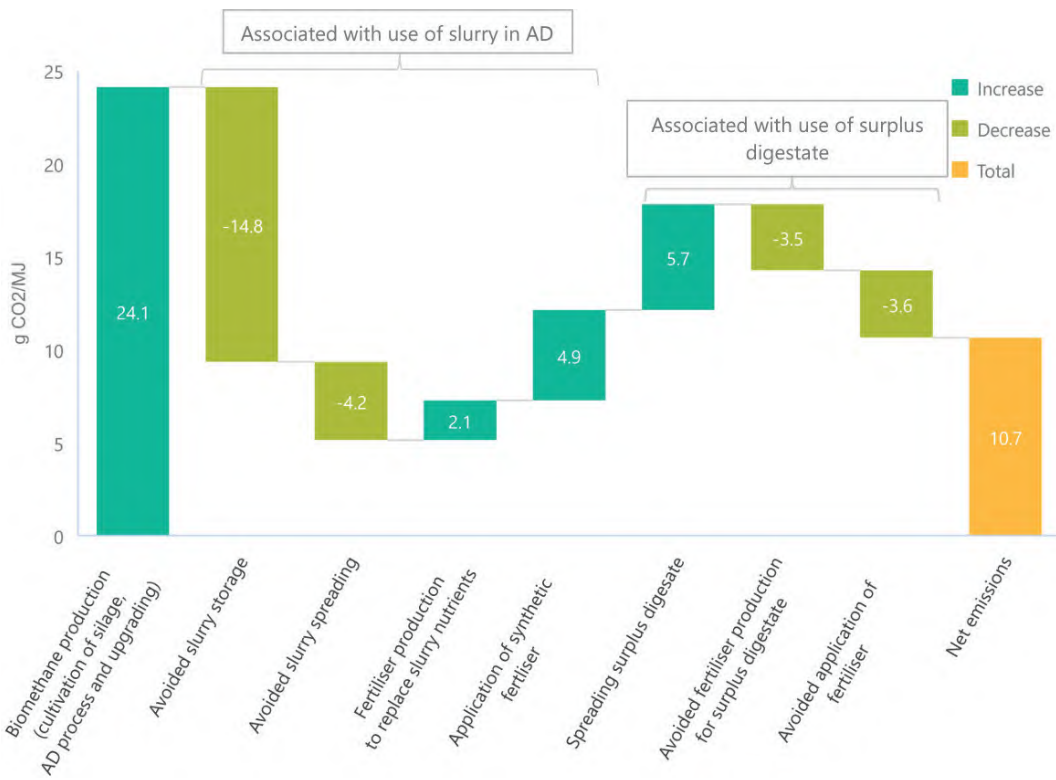


Figure 4.7 Lifecycle assessment of GHG emissions from 1MJ of biomethane. Source: SEAI (2022o).

The resource capacity can also be increased through the addition of green hydrogen. Such systems require cheap electricity and a cheap, concentrated source of CO_2 (e.g. from raw biogas). High emissions savings (potentially greater than 100%) versus diesel can be achieved when accounting for digestion of feedstocks, such as food waste, and the carbon recycling that occurs (Vo et al., 2017). To facilitate greater flexibility on the electricity grid, novel biogas reactors can adjust output according to electricity demand. Although this reduces the amount of gas produced overall, it means that it could be used as an effective back-up (Wall et al., 2016).

4.5.3 Liquid biofuels

Biodiesel is an established technology and generally turns bio-lipids (palm or rapeseed oil, tallow and others) into higher-quality diesel-like fuels through transesterification, known as fatty acid methyl esters (FAME) (Singh et al., 2019). All of the renewable content of diesel in Ireland is currently achieved with these biodiesels (Byrne Ó Cléirigh Consulting, 2022). However, their viscosity, density and water content are higher than fossil diesel, along with lower lubricity and oxidative stability (Bezergianni and Dimitriadis, 2013). There is then a relatively low limit (≤20%) as to how much can be blended in the general diesel supply before the fuel quality is adversely affected (Bezergianni and Dimitriadis, 2013). In fact, the EU fossil diesel standard EN 590 limits FAME to 7% (B7), although higher blends of up to 30% (B11–B30) are allowed in captive fleets through EN 16557, where high compatibility with current heavy goods vehicles has been noted (Kampman et al., 2013).

In response to the low blend limits and other shortcomings of biodiesel, renewable diesel produced through hydrotreated vegetable oils (HVOs) or other bio-lipids has gained prominence. HVO quality is much closer to that of fossil diesel, and the production process can be adjusted to meet stricter standards (Aatola et al., 2009). HVO can be either co-processed at a refinery or made in a stand-alone unit, and requires approximately 3.24MJ of hydrogen per litre of HVO or 9.5% of the energy content of the final product[17]. HVO's lower density means that greater than a c.30% blend in the summer or c.68% blend in the winter would mean that the fuel falls outside EN 590 standards without adjustment of the fossil component[18].

Biofuel supply and demand by 2030 will need to be significant to meet the proposed blending rates in transport: 10% for petrol and 20% in diesel (by volume). In a review commissioned by the Department of Transport and the National Oil Reserves Agency, Byrne Ó Cléirigh Consulting (2022) estimated that 72–78 million litres of bioethanol and between 570 and 730 million litres of biodiesel/HVO will be needed. In 2021, Ireland consumed c.200 million litres of biodiesel, which equated to a 6% blend (by volume). Approximately 23% of this (c.44 million litres) was produced from tallow, the majority of which was sourced in Ireland (25 million litres). This makes category 1 tallow the largest indigenous biofuel feedstock. To achieve a 20% blend, in the absence of indigenous HVO production, Ireland would be relying on HVO imports that could amount to between 4% and 5% of European HVO capacity (Byrne Ó Cléirigh Consulting, 2022).

4.6 District heating

District heating is a method of delivering thermal energy in the form of hot water through a network of highly insulated pipelines (Codema and BioXL, 2016). It works in much the same way as the electricity network. Just as the electricity system produces electricity at large plants and then distributes it to buildings, in a district heating system, heat is produced at large plants and transported over a network. This means that no fuel is burnt in buildings on the network, and instead a heat exchanger in each building transfers the heat energy from the network to the building's own water-based heating system, which can provide both space heating and hot water.

Once it is established, it is possible to connect multiple sources of heat, such as waste heat from electricity production and industry (Lake et al., 2017; Werner, 2017). It is estimated that there is enough heat currently going to waste from electricity production and large industries in Europe to meet all of Europe's current heating demand (Paardekooper et al., 2018).

In Denmark, district heating is seen as a key technology, providing whole energy system benefits, not just in the heating sector. It is proposed to connect the electricity and heat markets, in what is termed 'fourth-generation district heating' (4GDH) (Lund et al., 2014, 2018). The progression of the technology and system to 4GDH is explained in Figure 4.8. The new 4GDH systems that are currently being developed introduce an overall smart energy system, which facilitates higher shares

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[17] Figures adapted from a number of sources and represent a generalised equation (Sonthalia and Kumar, 2019).

[18] Density limits of 800–845kgm^{-3} in EN 590 (820–845kgm^{-3} in the summer). HVO and Fischer–Tropsch diesel have an average density of 780kgm^{-3}, without adjustment of the fossil component. A maximum blend of c.30% and c.68% would apply in the summer and winter, respectively ,including for 7% FAME at 870kgm^{-3}. A heavier fossil diesel (higher proportion of longer hydrocarbons) would allow increased blend rates within limits.

of renewables on the electricity grid through a combination of heating units powered by electricity and combined heat and power units producing electricity. These systems can be managed to be powered by electricity in hours of high renewable feed-in to the grid, and to produce electricity in hours of low renewable feed-in to the grid, utilising thermal storage when there is no demand for heat (Sorknæs et al., 2020). Thermal storage is a low-cost way of storing electricity for later use in the heating sector.

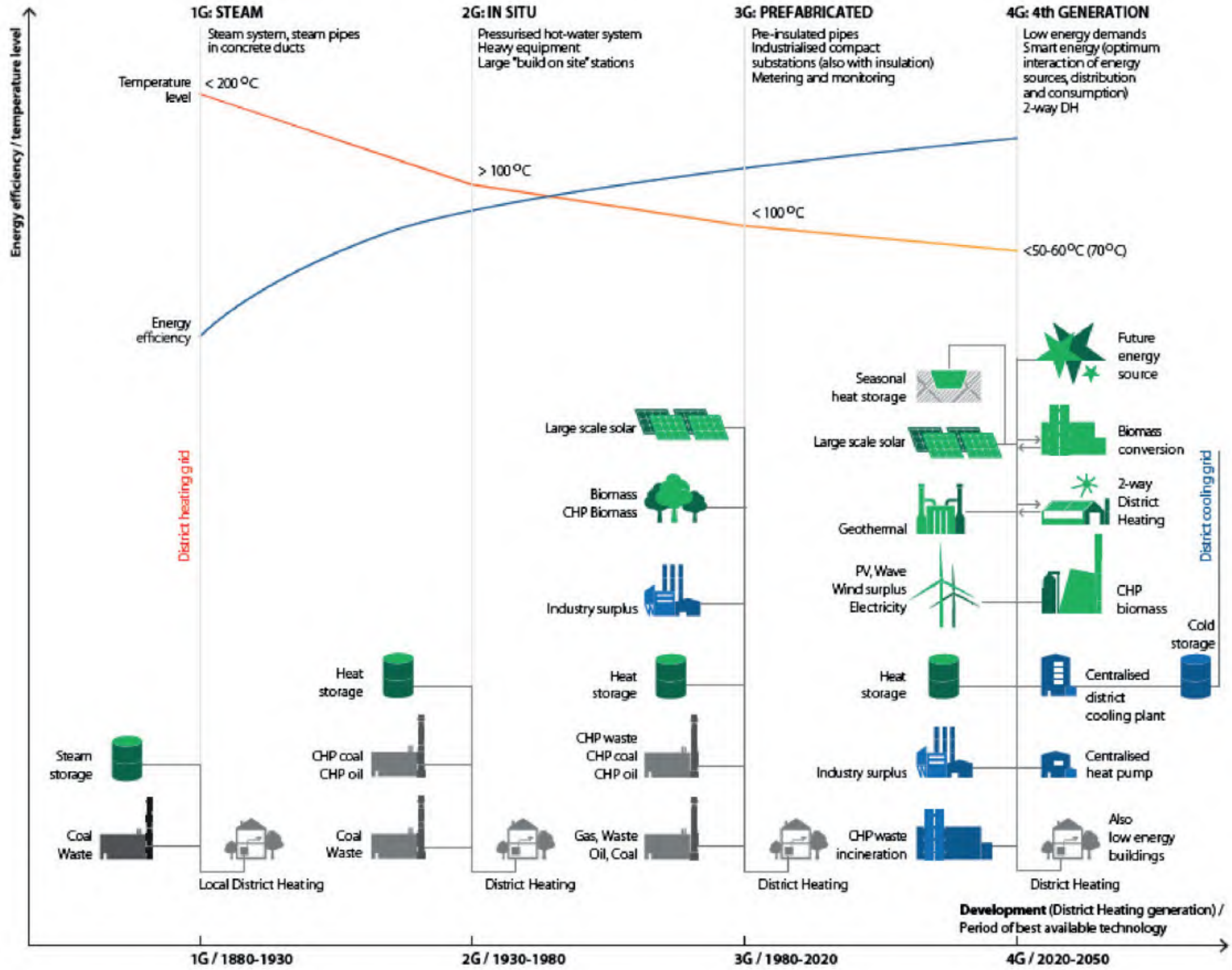

Figure 4.8 District heating progression 1880–2050. CHP, combined heat and power; DH, district heating. Source: Reproduced from Lund et al. (2014) with permission from Elsevier.

The SEAI national heat study found that district heating could play a significant role in achieving a net zero heating sector. It identified a potential to cover 50% of building heat demand by 2050 (SEAI, 2022k). There are currently six power stations and 17 industrial sites with the potential for waste heat extraction for district heating, with a potential to provide 1,800MWh of heat (SEAI, 2022k). The Climate Action Plan 2023 sets the target of delivering 2.5TWh of district heating by 2030. The Greater Dublin Area shows great potential for district heating, with a large amount of renewable and waste heat available (Codema, 2022).

4.7 The role of natural gas

Between now and 2030, natural gas will continue to be required in Ireland's electricity generation and heat sectors, but beyond 2030 the role of fossil gas is less certain. Between 2023 and 2030, there is expected to be an additional 2GW of gas power plant capacity added (Department of the Environment, Climate and Communications, 2022a; EirGrid, 2022). Looking to the future, there may continue to be a role for fossil gas in combination with CCS, and in creating green gases such as biomethane or green hydrogen. However, the extent of these roles deserves further consideration, particularly in the context of the ambition to achieve net zero by 2050 (SEAI, 2020b).

Gas Networks Ireland produced its 'Vision 2050' plan, which details an ambition to gradually displace the natural gas in its grid with a combination of renewable gas, abated natural gas and hydrogen. Both fossil hydrogen and green hydrogen are mentioned (see Annex A2.3 for an explanation of green hydrogen). The plan sees biomethane being injected into the grid from 2022, abated natural gas from 2028 and hydrogen from 2034 (Gas Networks Ireland, 2019). There are, however, several technical and economic challenges associated with replacing this natural gas with hydrogen. The lower energy density of hydrogen means that a 20% blend by volume will reduce emissions by just 8% for a given energy demand[19]. There are also issues with metering, steel embrittlement and gas quality consistency (Quarton and Samsatli, 2018, 2020). Still, studies have shown that hydrogen injection into the distribution network[20] is feasible, with downstream consumers less sensitive to gas composition (Quarton and Samsatli, 2018). In Ireland, the distribution network pipelines are made from polyethylene, which makes it 'hydrogen-ready' (NUI Galway, 2021, p. 23), and existing boilers can operate with a blend without modification. However, blending is not sufficient to achieve net zero emissions. Moreover, electric heating is more energy efficient and electricity is also less expensive than green hydrogen (see Chapter 5). Therefore, continued use of the gas grid with hydrogen is likely to be only an interim measure (on the way to a net zero system) and not a long-term solution (part of a net zero system). The literature review from Rosenow (2022), considering the use of hydrogen in heating for the UK, notes that, despite the significant attention hydrogen has received, the evidence does not support widespread use of hydrogen for space and hot water heating. Electrification and district heating are likely to be preferred where possible.

Within the power sector, Hickey et al. (2019), in reviewing future gas demand in Ireland's energy system with an 80% reduction in energy-related emissions, finds that higher network tariffs will be required for consumers in the future to cover network costs, even though gas consumption grows relative to current consumption levels in low-carbon scenarios with CCS. In the scenario examined it was found that the risk of stranding may not come from gas demand but from changes in regulation and how tariffs are allocated.

Across Europe, the share of gas in the European energy mix has declined from 23% of gross electricity production in 2010 to 16% in 2015 (McInerney et al., 2019). Stakeholders in the finance and banking industries, including central banks, regulators and credit rating agencies, have warned of the financial risk associated with being locked into fossil energy systems and have called for collective action to facilitate the role of the financial sector in achieving the objectives for the Paris Agreement. Consequently, gas-fired generation assets have become stranded and impaired. Stranded assets are defined as "assets that have suffered from unanticipated or premature write down, devaluations or conversion to liabilities" (McInerney et al., 2019, p. 4). Impaired assets are those whose value has been written off because the market value exceeds the current carrying value on the company balance sheet. A significant potential stranded asset risk for both generation and infrastructure assets in Ireland is identified by McInerney et al. (2019). The EU recently adopted an agreed taxonomy of what was considered to be a sustainable project as a means of guiding finance towards what was needed to meet 2030 climate objectives (European Commission, 2022b), and gas and nuclear energy were two controversial inclusions.

An assessment of Irish electricity and gas demand to 2050, commissioned by Friends of the Earth, concluded that, in the short term, "Delivering on the legally-binding Sectoral Emissions Ceiling for the power sector to 2030 requires an immediate increase in natural gas capacity (largely to replace existing, more polluting capacity) but at the same time, meeting carbon budgets will require a strong decrease in the utilisation of natural gas-fired generation later this decade" (Daly, 2022). In the long term, "Meeting the carbon budget programme means that, compared with 2020, natural gas demand in 2040 is reduced by 93% in the power sector, 85% in the residential sector and 67% in enterprise" (Daly, 2022, p. 4).

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[19] Assuming zero-carbon hydrogen production and equal usage efficiency.

[20] The gas grid is roughly divided into the transmission (high flow rates/pressure linking large towns and end users) and distribution (branches that service smaller more diverse users) networks (Gas Networks Ireland, 2015).

4.8 Hydrogen

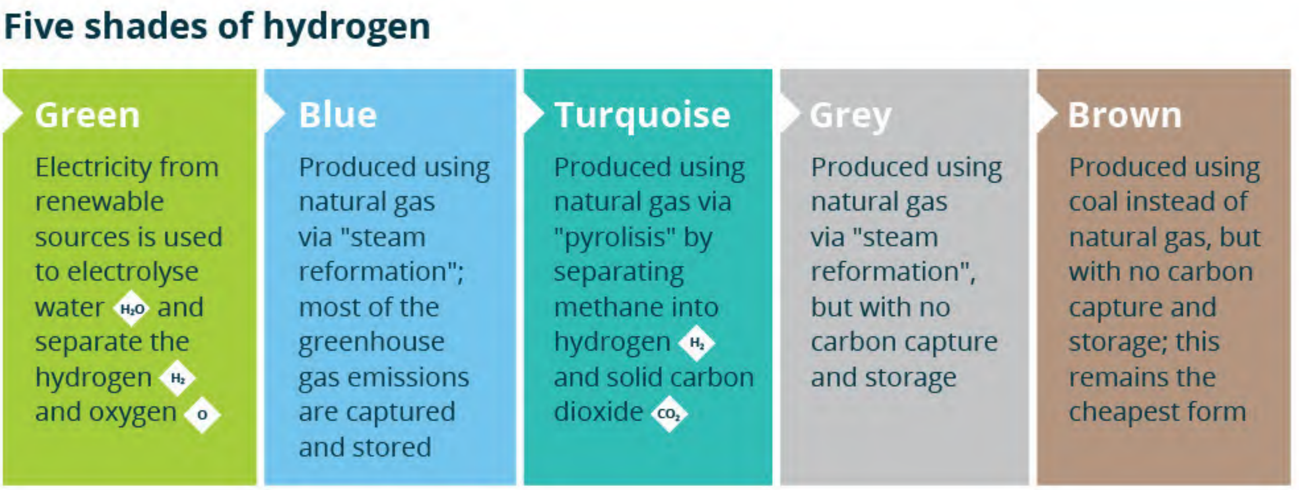

Figure 4.9 The different ways in which hydrogen can be produced.

As highlighted in a review by Hanley et al. (2018), most literature sees a role for hydrogen in the long-term decarbonisation of the energy system. Hydrogen can be used in a fuel cell for a range of purposes (Çabukoglu et al., 2019), injected into the natural gas grid (Gunawan et al., 2020) or used to make synthetic liquid and gaseous fuels (Runge et al., 2019). Ireland's significant potential for offshore wind provides a strong basis for the production of green hydrogen in Ireland (Rabiee et al., 2021) (Figure 4.9).

Paired with Ireland's offshore wind energy targets, green hydrogen could act as an energy storage medium (McDonagh et al., 2019a). The use of Ireland's abundant offshore wind resources could be optimised by creating a hydrogen supply network that complements the country's electricity system (Qadrdan et al., 2015; Lynch et al., 2018; IRENA, 2020a). Importantly, this would enable renewable electricity to generate emission reductions beyond the electricity sector (Hanley et al., 2018) and mitigate the issues of variability and storage associated with high penetration levels of wind and solar PV (Grueger et al., 2019). Offshore wind turbines could also be directly connected to electrolysis systems, transforming offshore wind farms into dedicated hydrogen production systems (McDonagh et al., 2020), and thereby avoiding additional strain on the electricity grid (Lund et al., 2015; EirGrid and SONI, 2020). However, this solution appears to offer the potential for only local constraint relief, and not dedicated MWh-scale storage suitable for offshore wind energy projects (Qadrdan et al., 2015; Quarton and Samsatli, 2020).

One study found that, even at 8.5% curtailment, a level that is greater than that projected for Ireland in 2030 (IWEA and Baringa, 2018), c.€4.5 profit per kilogramme of hydrogen is required to match the net present value of an offshore wind farm selling electricity to the grid (McDonagh et al., 2020). Even severe curtailment at 25% does not necessarily make hydrogen an attractive prospect. Even at this level of curtailment, a profit of €4kg^{-1} is still needed to match the net present value of the electricity-producing wind farm (McDonagh et al., 2020).

Only in the most optimistic scenarios is utilising surplus wind alone competitive and, in any case, it is dependent on the assumed opportunity cost, which varies from project to project. At low levels of curtailment, the cost of building electrolysis is greater than the losses incurred, especially at 'competitive' hydrogen prices. Free or very low-cost electricity does not necessarily lead to low-cost hydrogen, as the electrolysis capacity factor has a great effect on the levelised cost of hydrogen, essentially low run hours with free electricity produces a more expensive gas than higher run hours where electricity is purchased (McDonagh et al., 2018, 2019b).

Hydrogen production should still be connected to shore so that its full value chain can be captured in the integrated energy system (de Lagarde and Lantz, 2018). Being connected to the grid can allow the plant to potentially offer grid services (a potential additional revenue stream) and avoid the need for onsite batteries. Where grid congestion presents issues, an isolated hydrogen production system can allow an offshore wind farm to be developed where it may not otherwise have been permitted (Gea Bermúdez et al., 2021). Producing hydrogen alone may also allow for a less volatile revenue stream (via purchase agreements and the elimination of constraint/curtailment). However, in the absence of very generous subsidies and/or high hydrogen prices, electricity production remains more profitable (McDonagh et al., 2020). Up to 50% of the levelised cost of hydrogen comes from the cost of the electricity consumed (IEA, 2021b). Ireland is also not included in the proposed EU hydrogen backbone (Gas for Climate, 2021).

Green hydrogen can also be used to convert bio-lipids, including slaughterhouse wastes and used cooking oil[21], into renewable diesel, commonly known as HVO. Unlike traditional biodiesel, HVO more closely matches the properties of fossil diesel and is subject to less stringent blend limits (Neste Corporation, 2015). The hydrogen demand for this process is approximately 1MWh per thousand litres of HVO, or 10% of the energy content (Neste Oil, 2013; Sonthalia and Kumar, 2019). Hydrogen can also be used to produce synthetic methane[22], but this process, too, has a low overall efficiency; although there have been milestone projects in operation since 2013, the process has not yet seen widespread use (McDonagh et al., 2018; Rusmanis et al., 2019; Voelklein et al., 2019).

4.9 Ocean renewables

The oceans around Ireland and the Atlantic Ocean offer a significant renewable energy resource (Figure 4.2). However, ocean energy is not expected to play a role until post 2030 (Department of Communications, Climate Action and the Environment, 2020). Moving beyond 2030, it is expected that the cost of ocean energy technologies, such as wave and tidal, will become comparable to existing renewable sources, such as wind and solar PV, and therefore will undoubtedly play a part in the future energy mix.

Strangford Lough in County Down was the site for the world's first commercial-scale tidal energy project back in 2008. In September 2012, the Strangford Lough project hit an important milestone, with the developers SeaGen having produced 5GWh of tidal power since its commissioning, which is equivalent to the annual power consumption of 1,500 households (Renewable Technology, n.d.).

In June 2012, the Irish–Scottish Links on Energy Study (ISLES) reported on the feasibility of creating an offshore interconnected electricity grid, linking the three jurisdictions based on renewable wind, wave and tidal resources. It estimated an initial maximum resource potential of 16.1GW (12.1GW wind, 4GW wave and tidal) in the ISLES areas (Department of Communications, Energy and Natural Resources, 2014).

Several studies have identified potential areas suitable for wave (O'Connell et al., 2020) and joint wind–wave installations (Gallagher et al., 2016; Penalba et al., 2018; Gaughan and Fitzgerald, 2020). However, commercial deployment to date, both internationally and in Ireland, has been slow. Wave energy technology is not yet commercially viable and will require further investment in research and development (Lange et al., 2018b). Devices are at the demonstration and pilot level. Tidal energy technology is increasingly being proven viable; however, deployment has been slowed by marine governance challenges (Lange et al., 2018b).

4.10 Geothermal energy

Ireland has excellent shallow geothermal energy reserves all over the country. Our shallow (typically <100m) groundwaters provide a stable resource of thermal energy that can be used to provide heating at very high efficiencies through ground source heat pumps. For larger-scale developments, recent publications have shown that resources suitable for district heating, commercial and municipal applications are most likely to be found in the deeper parts of the Carboniferous basins in the east, Midlands and south-west of Ireland (Geological Survey Ireland, 2020). At present, there is insufficient data on Ireland's deep geothermal resource (below 400m), and so it has been considered for only shallow applications (up to 400m depth) through ground source heat pumps (SEAI, 2022k). However, with an improved understanding, it has significant potential through district heating.

Some of the key barriers to geothermal deployment are the lack of legislation and regulations, the risk and costs associated with identifying potential resources, and uncertainty over the ownership of it in Ireland (Vafeas, 2021). Ownership of

[21] Bio-lipids are fatty biological substances. Some, like rapeseed and palm oil, are commonly used to produce fuel. Strict criteria regarding the production of renewable fuels are laid out in the EU Renewable Energy Directive (European Union, 2018), and the use of waste products is viewed as inherently sustainable and a key part of a circular economy.

[22] This process is also known as power-to-gas: hydrogen from electrolysis is combined with a source of CO_2 to produce CH_4, the main component of natural gas, in a Sabatier reaction ($4H_2 + CO_2 = 2H_2O + CH_4$).

Ireland's geothermal resources has not yet been defined, but it could follow other existing models of private, public or mixed ownership within the EU. Following on from ownership of the resource is the issue of cost and risk (O'Reilly et al., 2022). Deep geothermal projects (for district heating) need significantly greater upfront capital expenditure than most other renewable technologies and also carry a lot of uncertainty. If a resource area that has been drilled for exploration is found to be unsuitable for a geothermal installation/development, the invested capital is lost.

Finally, there has been no clear policy to date. A draft Geothermal Energy Development Bill was submitted to the government in July 2010 and referred to the Office of the Attorney General and the Parliamentary Counsel, in response to an action item in the 2010 National Renewable Energy Action Plan. However, it was never introduced in the Dáil Éireann and the text is not publicly available. One of the action items listed in the 2015 government White paper Ireland's Transition to a Low Carbon Energy Future 2015–2030 is to "Establish a regulatory framework to facilitate the exploration for, and development of, geothermal energy resources" (Department of Communications, Energy and Natural Resources, 2015, p. 66), but it has not yet been drafted. While the lack of geothermal legislation does not necessarily preclude exploration for or development of geothermal energy, it does increase the level of risk and uncertainty for projects and potential investors. More recently, the Department for the Environment, Climate and Communications launched a consultation on the policy and regulatory framework for geothermal energy in Ireland (Department of the Environment, Climate and Communications, 2020).

4.11 Carbon capture, storage and removal

4.11.1 Carbon capture and storage

Ireland has potential to store CO_2 in its depleted gas fields (offshore Kinsale Head and Corrib gas fields). Price et al. (2018) assessed practical offshore capacity for geological carbon storage in Irish national territory to be c.455MtCO_2, while English and English (2022) estimate that the CO_2 storage capacities of the Kinsale Head and Corrib gas fields are 321MtCO_2 and 44MtCO_2, respectively.

There is no Irish research on the development of the technology. However, as with the global scenarios (section 1.2), it features in almost all the current net zero pathways (section 7.1). For an overview of the international research and development process, see section 1.2.4.1.

4.11.2 Carbon dioxide removal

CDR or negative emission technologies (NETs) will be needed to offset emissions in hard-to-abate sectors (e.g. agriculture, aviation or cement) that do not reach zero emissions. Recent research by Gaffney et al. (2020) has also highlighted the important role of NETs deployed in conjunction with high volumes of renewables to achieve not only emission reductions but also to contribute to the stable and reliable operation of the European power system. As explained in section 1.2.4.2, negative emissions can come in natural (trees or other carbon sinks) and technical forms (BECCS and DACCS).

Schenuit et al. (2021), from their review of CDR in nine countries, highlight that Ireland's policy has focused on forestry to date. Although afforestation is incentivised, Ireland remains characterised by low existing forest cover and has consistently missed afforestation targets.

McMullin and Price (2020a) provide a preliminary assessment of the overall potential for NETs in Ireland, the IE-NETs project. They determine a Paris-aligned CO_2 quota for Ireland as a maximum of 400MtCO_2 from 2015, or 180MtCO_2 from 2020. This national quota may be exceeded by 2024, which would contribute to a cumulative overshoot of 600MtCO_2 by 2050. The deployment of NETs is thus necessary to limit (and then reverse) such overshoot. The estimated aggregate potential for accumulated CDR (up to 2100) was found to be approximately 600MtCO_2. However, they stress that the practical potential is likely to be substantially less and recommend that a prudent policy for NETs potential in Ireland is to limit CDR dependence to no more than 200MtCO_2. Price et al. (2022) highlight that the extent of CDR reliance will be determined by the level of mitigation achieved in agriculture. McGeever et al. (2019), from an assessment of terrestrial capacity, found that, in contrast to other countries, Ireland has higher capacity for NETs options that are not currently available (DACCS and BECCS) and limited capacity for options available to be deployed at scale (afforestation, soil carbon management and biochar) due to the saturation of soil carbon stock and higher risk of reversibility due to impermanence. They recommend a policy focus on afforestation, with limited harvesting and eventual deployment of BECCS post 2035.

4.12 Nuclear energy

Within the international literature, it has been argued that nuclear power offers a very useful means of balancing a renewable energy system (Suman, 2018; Sadekin et al., 2019). Nuclear power plants operate 90% of the time, while onshore wind is around 35% of the time and fossil fuel power stations (coal or gas) can operate approximately 50–55% of the time; however, it can take up to 20 years to build a new plant (Muellner et al., 2021).

Within Ireland, the production of electricity by nuclear fission is prohibited under section 18 of the Electricity Regulation Act 1999, while the Planning and Development (Strategic Infrastructure) Act 2006 legislates against the authorisation of a nuclear fission power plant. However, at times, small amounts of nuclear generated electricity are imported from the UK.

There have been renewed calls for nuclear energy to be examined as energy security concerns came to the fore following Russia's invasion of Ukraine (House of Oireachtas, 2022). The group 18for0 have called for investigation into small modular reactors (<300MW), which it claims could facilitate decarbonising Ireland's power sector by 2037 by integrating 18% of nuclear energy to complement the remainder from renewable energy (18for0, 2020). The group identifies two reactors at a later stage of development:

- the NuScale pressurised water reactor (design certification was approved in the USA in 2020);
- the GE-Hitachi boiling water reactor (undergoing licensing in the USA and Canada).

5

Future Energy Choices by Sector

Key messages

Improving the energy performance of buildings is a key decarbonisation measure. This offers important co-benefits in reduced fuel costs and improved comfort and health.

For Ireland's housing, the dominance of fossil fuels in home heating, the large size of homes and the number of one-off houses means that the energy demand per capita is higher than that of other EU countries.

The energy and performance of industry and services has not been well covered in academic analysis to date. Research has primarily focused on the food and beverage and pharmaceuticals sectors.

Transport is a challenging sector. For private travel, a transformative shift to active modes is required to reduce our car dependence, along with the uptake of electric vehicles. The options for heavy-duty vehicles are less well established and have lacked policy coverage to date.

Compact development will be important to minimise the emissions associated with new developments. Retrofitting older buildings is an important means of reducing the demand for cement while also supporting town revitalisation and safeguarding cultural heritage. In addition, more compact developments can support active travel modes.

5.1 How we move around: transport

Electrification features heavily in all plans to reduce transport emissions (Chapter 7). There are two main reasons for this: first, wind and solar are the renewable technologies that are most advanced and both primarily produce electricity; second, technologies such as heat pumps and EVs that use electricity are more efficient than the alternatives (section 4.4). In addition, electricity is associated with much less air pollution and other concerns associated with bioenergy. Batteries are currently a more attractive option than hydrogen and fuel cells for light-duty vehicles. Hydrogen or hydrogen-derived synthetic fuels may have a more important role in heavy-duty vehicles, shipping and aviation (IPCC, 2022b).

Over time the accepted least-cost solutions to transport emissions have changed. Compressed natural gas (CNG) was proposed to displace diesel (Thamsiriroj et al., 2011; Daly and Ó Gallachóir, 2012), particularly in light goods vehicles (LGVs) (Mulholland et al., 2016). However, closer inspection of the life cycle emissions of natural gas (Kollamthodi et al., 2016; Cai et al., 2017), little progress in building biomethane capacity (section 4.5.2) and greater reduction targets mean that replacing diesel with natural gas will be insufficient in the context of achieving net zero emissions (Mulholland et al., 2018b). Advances in EVs combined with progress in renewable electricity, too, have shrunk the space available for CNG or biomethane. However, it remains important in heavy goods vehicles (HGVs) where some infrastructure is already in place and the abatement cost is favourable (Rajendran et al., 2019).

5.1.1 Private travel

Ireland is heavily reliant on private car travel to get around. In 2021, private car travel represented 43% (21TWh) of total transport energy demand (48TWh) and was one of the most significant contributors across all sectors, accounting for 16% of Ireland's total energy demand (133TWh) (SEAI, 2022g). Research by Lowans et al. (2022) analysed transport poverty (lack of mobility services necessary for participation in society) via a survey of 1,564 participants across Ireland, which showed 18% transport poverty among the participants.

In 2008, VRT was changed from a tax based on the car sale price to one based on the emissions class of the car. Prior to this, petrol cars dominated the car fleet, but, since then, with the tax essentially incentivising the more efficient diesel engines, there has been a significant flip. Diesel cars went from being less than 30% of new sales in 2007 to consistently around 70% of new sales between 2010 and 2018 (O'Riordan et al., 2021b). Another worrying trend is the growth in popularity of larger cars (sports utility vehicles, SUVs). In 2021, SUVs accounted for 55% of new car sales, while EVs accounted for just 8% (Daly and O'Riordan, 2022). SUVs' greater weight and height mean that they emit around 20% more CO_2 than medium-sized cars, and far more than EVs.

In 2019, travel for work accounted for the largest overall passenger transport demand (30%), followed by shopping (19%) and companion journeys (e.g. the school run) (16%) (Figure 5.1; O'Riordan et al., 2022). Another important consideration is that journeys of under 8km were responsible for 37% of passenger transport emissions (O'Riordan et al., 2022).

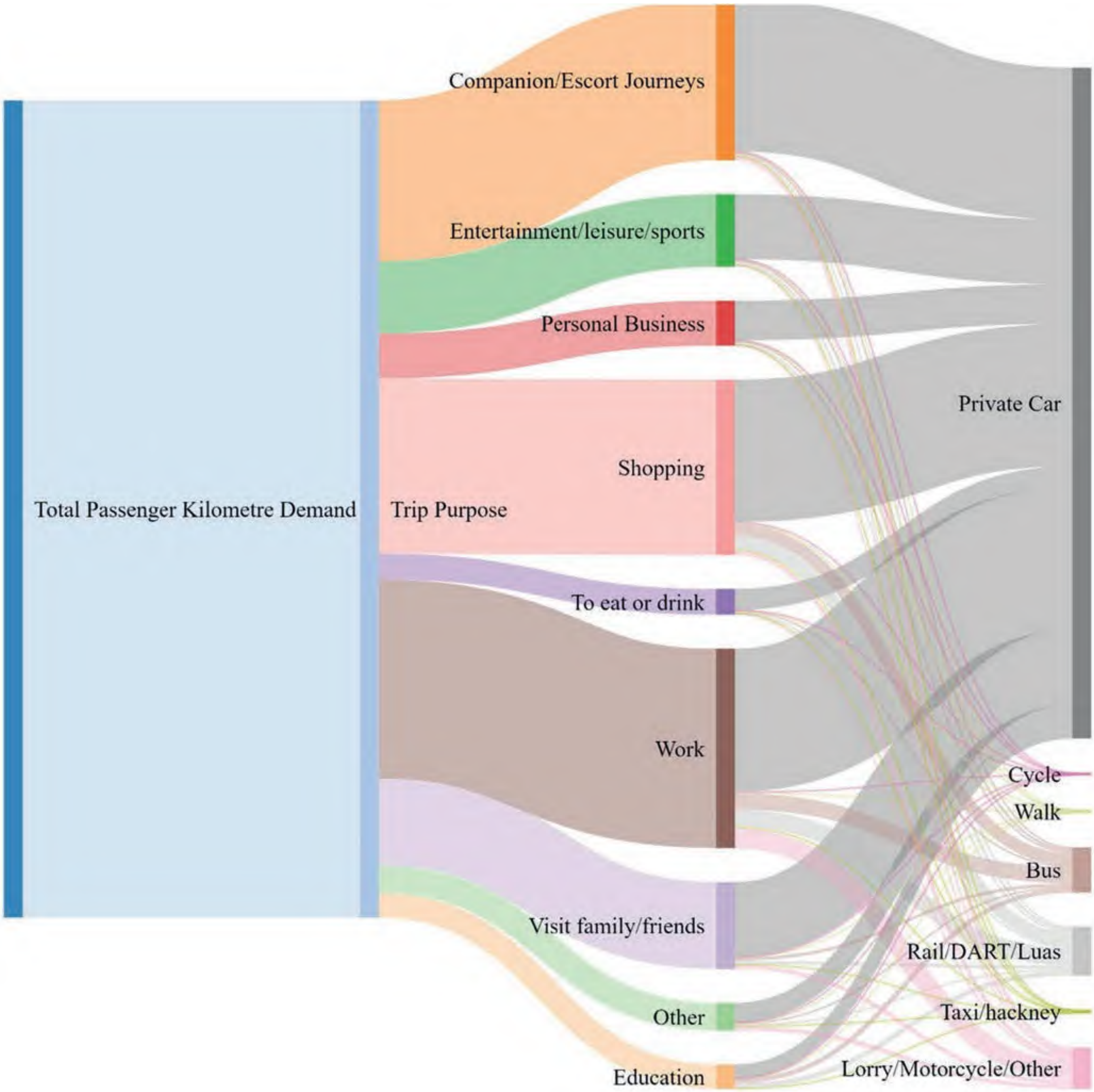

Figure 5.1 How and why we travel: passenger-kilometres by trip purpose and mode. Source: O'Riordan et al. (2022). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

With regard to individual travel, a key framework for understanding transport policy measures is avoid–shift–improve. This is a decision hierarchy that prioritises avoiding the need for travel or shifting to active/public modes over making improvements to our cars or other vehicles (Figure 5.2). The purpose of designing transport policy in this manner is to reduce the overall need for private car travel, which is the least efficient way to transport someone. It focuses predominantly on urban areas, where it is easier to design higher-density development. The principle is also applicable in rural areas, although more difficult to implement. Moving forward the National Planning Framework priority of compact growth seeks to undo years of developer-led planning in Ireland that has resulted in very low-density development and significant urban sprawl.

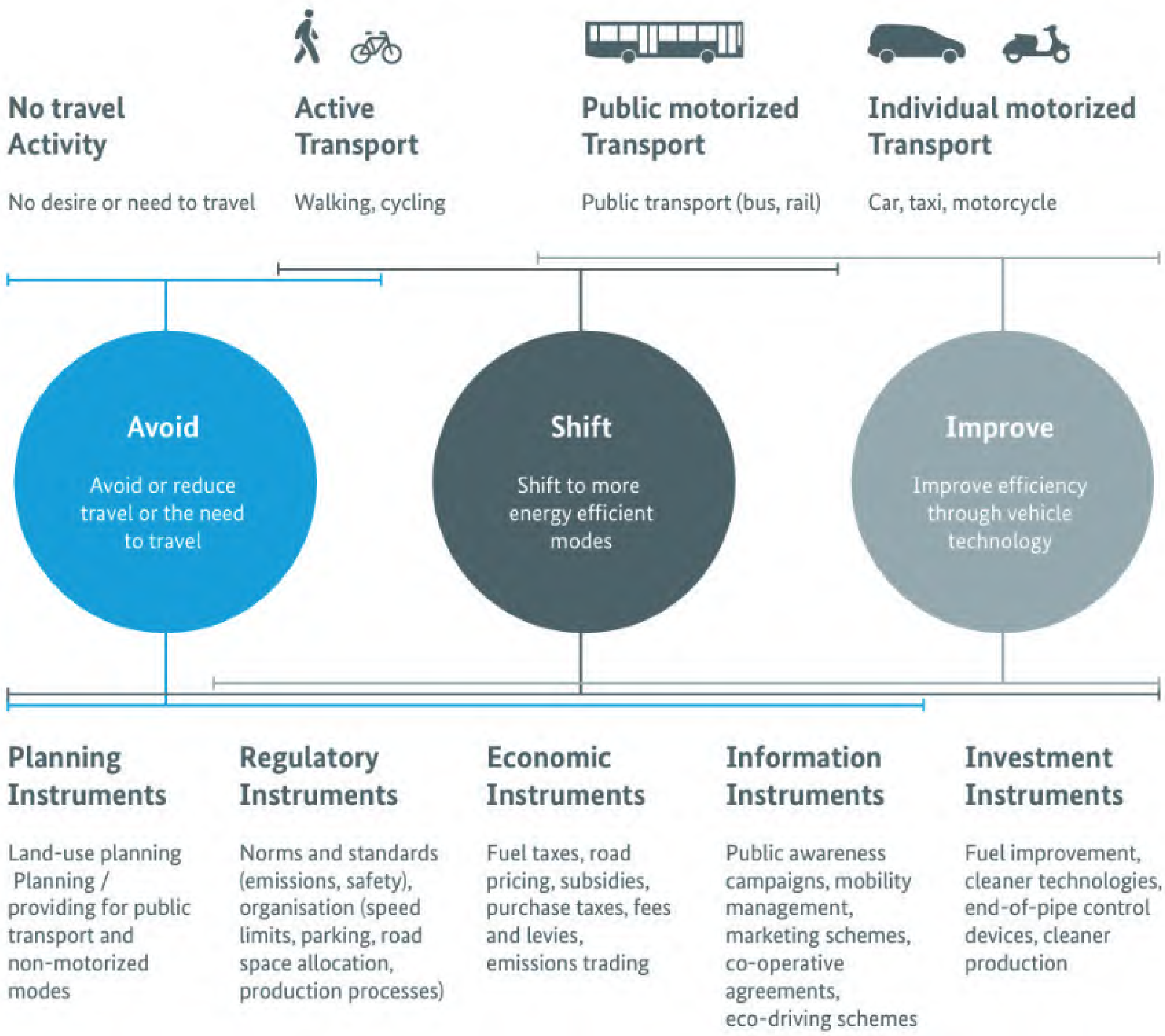

Figure 5.2 Transport policy decision hierarchy: avoid–shift–improve. Source: Bongardt et al. (2019).

Another interesting concept in urban design that puts emphasis on reducing the need for travel is the ‘15-minute city’ (Moreno, 2019; Moreno et al., 2021). Originally proposed in 2016, it grew in popularity as a concept during the COVID-19 lockdowns (Moreno et al., 2021; Allam et al., 2022a). It proposes a reimaging of our cities so that we can live, work and enjoy leisure all within a 15-minute walk or cycle. This would not only help to reduce transport-related GHG emissions and air pollutants but also bring other important health and quality-of-life benefits (Allam et al., 2022b). There is an increasing call for a focus on mobility as opposed to travel when considering private travel options (Figure 5.3).

Until recently policy within Ireland was narrowly focused on vehicle efficiency and electrification (‘improve’). However, as outlined by O’Riordan et al. (2022) and the Organisation for Economic Co-operation and Development (OECD, 2022), it will need to be much more ambitious, with efforts to reduce overall demand (‘avoid’) and a move to public/active modes of travel (‘shift’).

First, on the question of vehicle efficiency improvements, it is now well established that these have been overstated by the industry. In Ireland, looking at the changes in labelled fuel consumption (litres per 100km travelled) versus the actual fuel consumed in Ireland, Dennehy and Ó Gallachóir (2018) showed that the improved efficiencies in test values were cancelled out by the ‘on road’ factor. Their bottom-up estimate for the Irish car fleet showed that published test figures underestimated the amount of fuel consumed by 30%. In other words, the cars perform better only during tests and are still consuming the same amount of fuel on the road. At an EU level, the International Council on Clean Transportation found that in Europe the difference between test values and actual on-the-road consumption had increased from roughly 9% in 2001 to 42% in 2015 (International Council on Clean Transportation, 2017).

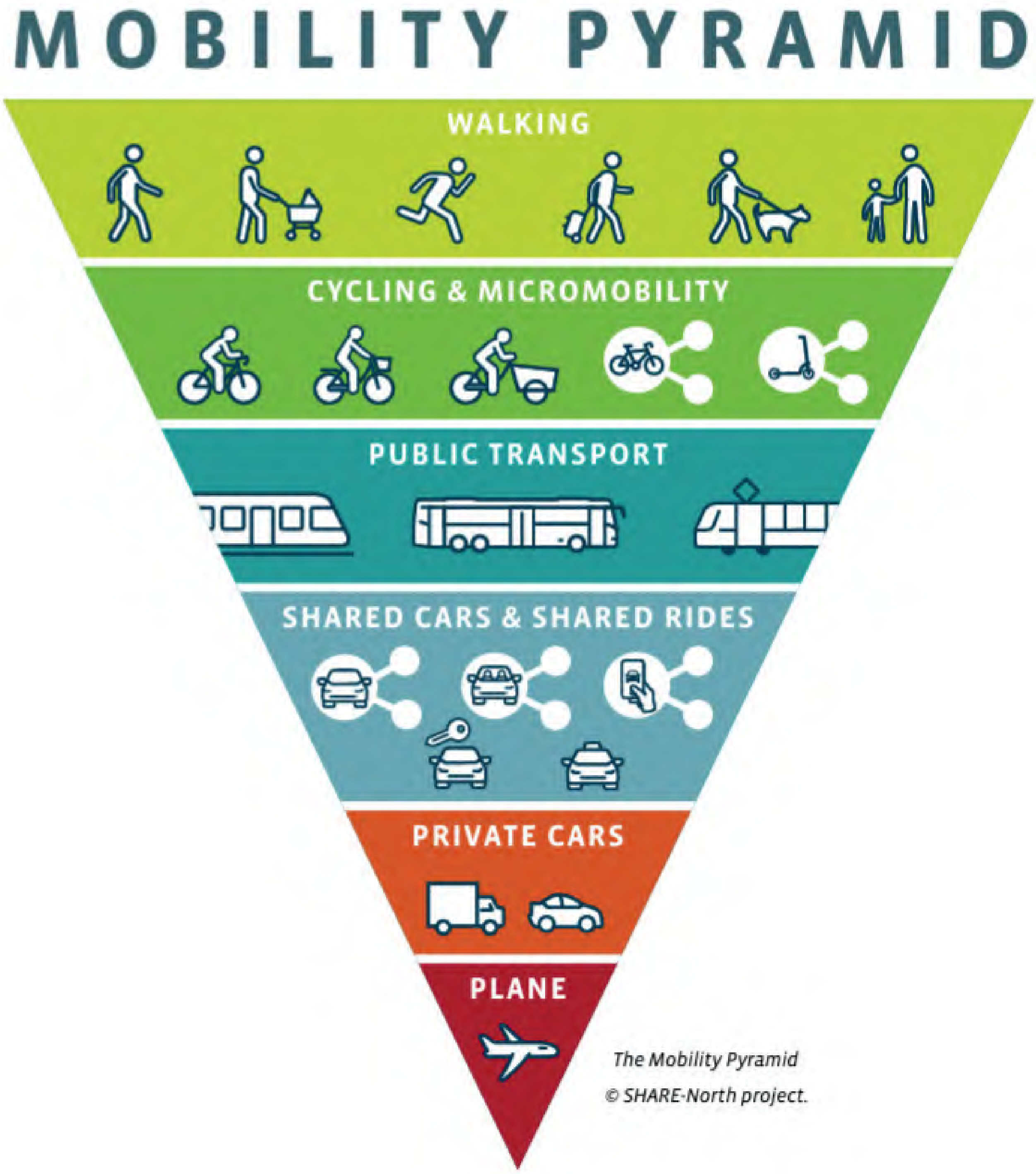

Figure 5.3 The Mobility Pyramid. Source: Karbaumer et al. (2021).

The contribution of EVs to decarbonisation is a little more nuanced. Based on a spatial analysis of the availability of transport options, Carroll et al. (2021) highlight that the majority of Ireland is highly dependent on cars. EVs are thus seen as an important means of decarbonising transport for our dispersed population. However, research has shown that EVs are not going to these households. By examining the distribution of EV charger grants, Caulfield et al. (2022) showed that EVs are most concentrated in more affluent urban areas within Dublin where there are better alternatives for active and public transport. This points to a growing income and equity gap, which will see those most impacted by rising fuel prices (section 3.4.3) least able to move to EVs. While the upfront purchasing cost of EVs is higher than that of conventional ICEs, they have significantly cheaper running costs (Weldon et al., 2018).

In addition to being an equity issue, this also presents a significant challenge for the electricity grid, as the areas identified for high EV uptake are primarily on the east coast or in urban centres, while the majority of renewable generation (i.e. wind resource) is on the west coast and in rural areas. Pillai et al. (2022), from a spatial analysis of purpose of vehicle use, show that urban areas (Cork and Dublin) have the highest density of potential EV adopters. Similarly, Aryanpur et al. (2022), from a spatial analysis of EV adoption up to 2030 based on household incomes, found that the Greater Dublin Area would have the highest concentration of EV adoption. Another critical finding from this study was that none of the scenarios for 2030 achieved a 51% reduction in private transport emissions. Even the highly ambitious scenario with widespread EV adoption, increased biofuel blending and modal shift on shorter journeys fell short, thus reiterating the need for a range of more transformative interventions.

Public transport is generally preferable to private cars in terms of emissions, as the greater fuel use of a bus or train is more than compensated for by the additional passengers. Therefore, the emissions per passenger are much lower than that of cars. Buses make up 0.2% of vehicles in Europe but deliver 10% of passenger-kilometres (Mulholland and Rodríguez, 2022) and have a higher share of zero-emission vehicles than cars. However, Ireland lags behind its neighbours, with the majority of the bus fleet still diesel (Mulholland and Rodríguez, 2022).

Gunawan et al. (2021) examined the potential for green hydrogen produced from a system of wind, on-site solar PV and battery storage to power the current bus fuel demand for Dublin, Cork, Limerick, Galway, Waterford and Belfast. They found that hydrogen produced, transported and dispensed using this system could meet the entire bus fuel demand in all the cities studied, at a potential levelised cost of hydrogen (LCOH) of €5–10 per kilogram. They conclude that the future operational cost of fuel cell electric buses (FCEBs) in Belfast, Cork and Dublin can be competitive with diesel buses, especially if carbon taxes are increased to reflect the true cost of fossil fuels. The operational cost parity of diesel -and hydrogen-fuelled buses could be achieved by 2030 in Dublin.

With active transport such as walking or cycling, the emissions benefits are clear. However, in order for there to be realistically viable alternatives to the private car, significant improvements in infrastructure are needed. The delivery of this infrastructure is contingent on changes in our approach to spatial planning (as outlined in National Planning Framework) that will ensure that the new homes and jobs of our growing population are designed to facilitate active travel. Dey et al. (2019) highlight that we are likely to be underestimating the positive effect on air quality of replacing private car trips with public transport, walking or cycling. Driving style, trip length, speed and other factors can have a large effect (–58% to +76%) on non-CO_2 emissions from ICEs, with shorter trips (taking place in urban areas) tending to release more emissions than longer ones.

In the case of the 'avoid' approach, continuing a COVID-19 trend, O'Riordan et al. (2021a) have modelled scenarios to look at the impact of remote working. A report from the OECD identifies transformative policies that can help Ireland adopt the 'avoid' approach (OECD, 2022). Otherwise, research in this area is limited.

5.1.2 Road freight

Road freight transport is a key enabler of global economic activity while also a central consumer of fossil fuels (Mulholland et al., 2018b), with the fleet in Ireland almost exclusively fuelled by diesel. Road freight transport consists of LGVs with an unladen weight of less than 2 tonnes or gross weight less than 3.5 tonnes, and HGVs with an unladen weight of more than 2 tonnes or gross weight of more than 3.5 tonnes (Teter et al., 2017; Gray et al., 2021). In 2021, HGVs accounted for 19% of transport energy demand and LGVs 7% of transport energy demand (SEAI, 2022g). Together the two account for 28% of diesel demand (SEAI, 2022g). In 2020, there were 377,890 goods vehicles registered in Ireland, of which 337,236 were LGVs and 40,654 were HGVs (Department of Transport, 2021b). This number has been growing rapidly and presents a significant decarbonisation challenge. Yana et al. (2020) project that Irish road freight activity (measured in million tonnes per kilometre) could double from 13,080Mtkm^{-1} in 2015 to approximately 26,000–27,500Mtkm^{-1} in 2050.

Low-carbon freight policy measures in Ireland have been largely absent compared with measures for the public transport sector (Zhang et al., 2022). Previous climate action plans featured only targets for public buses and LGVs. However, the more recent Climate Action Plan 2023 includes an interim target of 700 low-emission HGVs by 2025 and 3,500 by 2030 (Department of the Environment, Climate and Communications, 2022a). Despite the lack of policy, since the Irish haulage sector is a competitive environment with low margins (3–5%), cost reductions have driven energy improvements (Islam, 2019).

With HGVs and logistics, as well as changes to the vehicles (aerodynamics, reducing weight, engine efficiency/hybridisation), systemic changes (route optimising, improved loading and others) can provide additional emission reductions by reducing distance travelled per unit of freight (Mulholland et al., 2018b). Increasing the energy efficiency of vehicles is important to reduce interim emissions, but we must ultimately shift to zero-carbon solutions.

As with passenger cars, international research has shown that when suitable BEV options are available, they are likely to be preferred over hydrogen-based technologies (Heid et al., 2017). An LGV requires relatively little energy and is therefore well suited to electrification. However, HGVs require significant energy. This high energy demand, paired with very heavy batteries and poor energy density (compared with liquid fuels), make the electrification of HGVs difficult without major technological breakthroughs. For the largest vehicles[23], which typically have much greater daily mileage, hydrogen has several key advantages (Gray et al., 2021). Most importantly, it can offer refuelling practices similar to diesel and natural gas, with similar range and performance (Çabukoglu et al., 2019).

Within Irish research, biogas (Long et al., 2021a; Keogh et al., 2022a) and hydrogen (McDonagh et al., 2019a; Gray et al., 2022; Gunawan and Monaghan, 2022) have each received interest as a means of decarbonising HGVs. Gunawan and Monaghan (2022) provide an assessment of electrification or hydrogen as options to decarbonise trucks in the quarrying sector. McDonagh et al. (2019a) investigated the potential cost of producing hydrogen from curtailed wind energy and conclude that, while it has no role in smaller vehicles, there is potential for HGVs. Gray et al. (2022), in an assessment of HGV decarbonisation options, found that for vehicles with a range of less than 450km, BEVs achieve the lowest total cost, while for vehicles that require a range of up to 900km, hydrogen fuel cell vehicles represent the lowest long-term cost of abatement.

Zhang et al. (2022) developed an adaptation of the avoid–shift–improve framework for road freight in Ireland. They note that it differs from the treatment of passenger transport. In the case of 'avoid', instead of removing the need for freight, the aim may be to reduce the number of shipments or trip distance (Pfoser, 2022) and manage the growth in freight transport demand (McKinnon, 2018). For the 'shift' approach, 'consolidation' in supply chain management principles has been suggested to combine transport modes smartly (McKinnon, 2018). Additionally, in a passenger context, 'shift' refers to a move to public or active travel, but in the freight transport context the shift approach might also indicate a shift to a cleaner fuel option within the same transport mode category.

5.1.3 Shipping and flying

International aviation and shipping are not currently included in Ireland's national emissions accounting. Countries have been unable to agree how these cross-border activities will be included within NDCs (Schneider et al., 2020). As a result, only domestic flights and boat trips (separate to fishing) are included under transport in the national inventory report that must be submitted to the UNFCCC (EPA, 2022f). The UN bodies responsible for the aviation and maritime sectors are the International Civil Aviation Organisation (ICAO) and the International Maritime Organization (IMO).

5.1.3.1 Aviation

In 2019, prior to COVID-19 disruptions, aviation accounted for 21% of Ireland's transport energy demand, totalling 13TWh, which was split between international (12.9TWh) and domestic (0.07TWh) aviation (Table 5.1; SEAI, 2022g). During 2020 and 2021, aviation dropped to around a third of pre-pandemic levels, accounting for 10% (4.6TWh) of transport energy demand in 2020 and 11% (5.2TWh) in 2021 (SEAI, 2022g).

Table 5.1 *Energy demand (GWh) and CO_2 emissions ($ktCO_2$) from Ireland's international and domestic aviation, 2018–2021*

	2018	2019	2020	2021
Energy demand				
Domestic aviation	65	70	31	33
International aviation	12,769	12,914	4,606	5,160
CO_2 emissions				
Domestic aviation	17	18	8	9
International aviation	3,282	3,319	1,184	1,326

Source: SEAI (2022g). Emissions conversion based on SEAI (2022f).

[23] Defined here as having an unladen weight of greater than 10 tonnes.

As with haulage, aviation is dependent on a single fuel, but, unlike haulage, no clear alternatives to jet fuel (kerosene) have yet been identified. A reduction in flying activity is thus the only clear option for reducing emissions.

Industry groups have put forward decarbonisation strategies, which assume a large uptake of 'sustainable aviation fuel' in the form of either hydrogen or bioenergy. They also rely on a significant proportion of offsetting. The International Air Transport Association (IATA), representing some 290 airlines or 83% of total air traffic, has proposed a net zero strategy that relies on sustainable aviation fuel for 65% of the reductions and offsets, plus carbon capture for another 19% (IATA, 2021). Similarly, the EU aviation sector proposes using bioenergy and hydrogen (Royal Netherlands Aerospace Centre, 2021). The International Council on Clean Transportation offers alternative scenarios, with reductions in aviation demand to avoid the need for offsetting (Graver et al., 2022).

Bauen et al. (2020) reviewed the range of sustainable aviation fuels available and concluded that producing so-called renewable 'drop-in' kerosene is the most attractive option because it does not require modification of the aircraft airframe and engine and refuelling infrastructure. Why et al. (2019) proposed growing algae to produce bioenergy jet fuel. However, stringent requirements on jet fuel leave little room for innovation and limit the use of certain fuels, such as HVO (section 4.5.3) and fuels produced using the Fischer–Tropsch process (section 4.8), to 50% of jet fuel (Gray et al., 2021). Hydrogen is a very appealing fuel that can be derived from a range of renewable sources and produced from fossil sources with CCS, but its use in medium- and long-haul aircraft requires a radical redesign of the engine and airframe, as well as the fuel supply chain, including on-the-ground storage and refuelling, leaving it a prospect for the long term. Alongside the technical barriers to producing the aircraft itself, the airport operations required to store and refuel with liquid hydrogen would have to be developed and extensively tested (Baroutaji et al., 2019).

As an island, there is little room to avoid refuelling aircraft in Ireland, meaning that a substantial indigenous demand for such fuels will continue. There is very little Irish research in this area. However, in 2021, Trinity College Dublin launched the Sustainable Aviation Research Centre, funded by Ryanair (Trinity College Dublin, 2021).

5.1.3.2 Maritime

In contrast to aviation, the shipping sector has not committed to net zero emissions by 2050. The most recent GHG strategy, released back in 2018, proposed to cut annual GHG emissions from international shipping by at least half by 2050, compared with their level in 2008, and work towards phasing out GHG emissions from shipping entirely as soon as possible in this century (IMO, 2018). A new strategy is due in 2023.

Despite carrying 80–90% of global trade by volume (Balcombe et al., 2019), maritime shipping has until recently represented an emissions blind spot, with the first reduction targets announced only in 2018 (IMO, 2018). Although demand for maritime transport is growing, the sector is aiming for a 40% reduction in global emissions intensity[24] by 2030, and an overall 50% emissions reduction by 2050 when compared with 2008 figures (IMO, 2018). The international nature of the sector makes estimating energy consumption difficult, however. Figures can be based solely on the fuel purchased, or all the fuel consumed in a country's territory. By one estimate, Ireland is thought to have consumed 11.5TWh of energy in shipping in 2018 (Gray et al., 2021), while another study suggests a demand of 3TWh in 2050 (Brandt et al., 2016), which reflects the uncertainty inherent in these calculations[25]. However, given that the average lifespan of a shipping vessel is 30–40 years, both estimates suggest significant and sustained demand for low- and zero-carbon fuels compatible with new and existing ships (Horvath et al., 2018; Gray et al., 2021).

Liquefied hydrogen can be burned or used in a fuel cell with similar efficiencies for marine applications (Horvath et al., 2018). The cost and difficulties associated with the retrofitting of ships and the construction of additional infrastructure represent significant challenges (Gray et al., 2021), but hydrogen fuels in shipping are expected to be competitive with fossil fuels by 2030, and have lower overall costs by 2040 (Horvath et al., 2018). Shipping, then, is a sector that could provide a large market for renewable hydrogen.

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[24] Carbon emissions per unit of transport work, e.g. tonnes of CO_2 per tonne of cargo.

[25] Neither reference provides detailed calculations or traceable sources for their final figures.

5.2 In our buildings

5.2.1 In our homes: residential

Improving the energy performance of our homes is one of the most important policy measures for a timely decarbonisation because of the very long lifespan of buildings. In the context of buildings, a retrofit refers to one or more upgrades designed to reduce energy demand. This involves measures such as adding insulation, sealing leaks, replacing windows/doors and installing a new heating system. Retrofits offer many benefits beyond reduced emissions, such as lower heating bills, higher levels of comfort and increased home value.

In 2020 the average home used 20,955kWh of energy – split into 76% from direct fuel (non-electric) and 24% from electricity. This 76:24 split of energy sources has been steady since 2011 (SEAI, 2021d).

5.2.1.1 Understanding home energy improvements

The measure of a building's energy performance in Ireland is known as a Building Energy Rating (BER). This was introduced under the EU Energy Performance of Buildings Directive (2018/844/EU) (Recast), which required each country to develop an energy performance certificate. As with energy labelling on electrical applications, the BER is a coloured scale from A to G, with A being the most energy efficient and G the least energy efficient (Figure 5.4). The rating is based on an assessment of the home's building elements (e.g. walls, doors, windows, heating system) and simulation of how much heat energy will be required to maintain a comfortable indoor temperature.

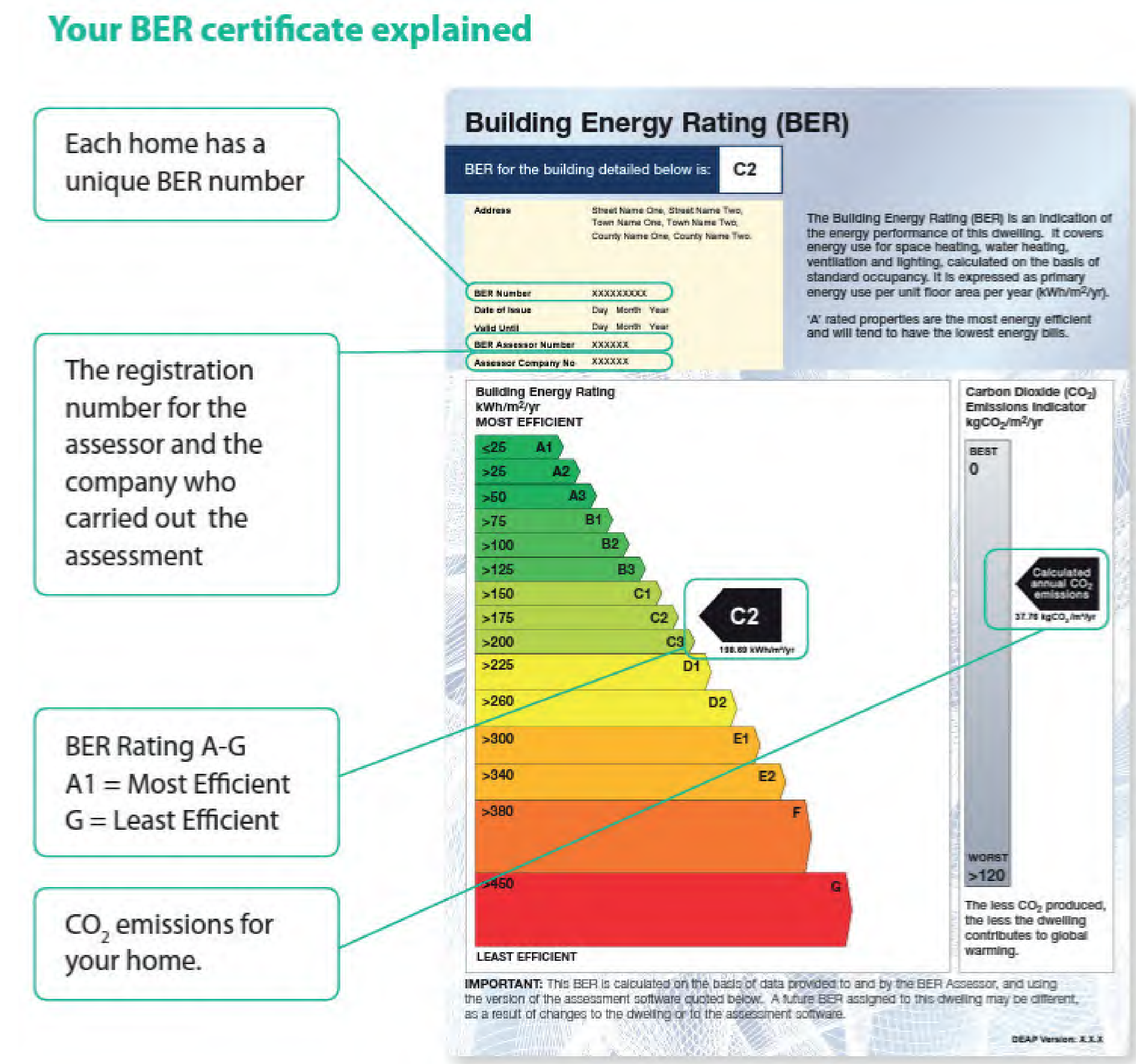


Figure 5.4 Explanation of a BER certificate. Source: SEAI (2021a).

In understanding the energy performance of the building stock, a well-documented issue is the gap between the BER and actual energy performance of the building (Ahern and Norton, 2020; Ali et al., 2020; Beagon et al., 2020; Coyne and Denny, 2021a; SEAI, 2022d). Coyne and Denny (2021a), from a sample of 9,923 Irish homes, found that the BER overestimated energy demand in the least energy-efficient dwellings (D, E, F and G rated), with an average difference ranging from 24% for D-rated homes to 56% for F- and G-rated homes. Conversely, the BER underestimated energy demand in dwellings with higher energy efficiency (A and B rated): the energy demand of these homes was on average 39% greater than BER estimations. However, it remains a useful means to categorise houses and benchmark the quality of energy performance across the housing stock.

Ireland is an interesting case given the high reliance on oil as a heating fuel, the dispersed pattern of residential housing and the relatively poor energy performance of the existing housing stock (Mac Uidhir et al., 2020b). The energy efficiency of Irish homes measured in heating energy demand per square metre ($kWhm^{-2}$) is better than the EU average (Figure 5.5). Nonetheless, the dominance of fossil fuels in home heating, the large size of Irish homes and the number of one-off houses mean that the total energy demand or CO_2 emissions per capita is high. In 2019, Ireland had one of the highest level of GHG emissions from home heating, at around 1,200kg per capita compared with the EU average of around 700kg per capita (Eurostat, 2020).

Ahern and Norton (2019), based on an assessment of the homes in Ireland's building energy performance certificate (known as BER) database from 1995 to 2014, conclude that the often-made assumption that the majority of dwellings in Ireland are of a poor energy efficiency standard is invalid. However, in another study, Dennehy et al. (2019), looking at a broader range of factors behind changes in space heating, highlight that the economic recession was responsible for most of the fall in space heating demand rather than the national energy efficiency retrofit programme. They conclude that savings associated with the retrofitting schemes may constitute only a small proportion of the total energy savings.

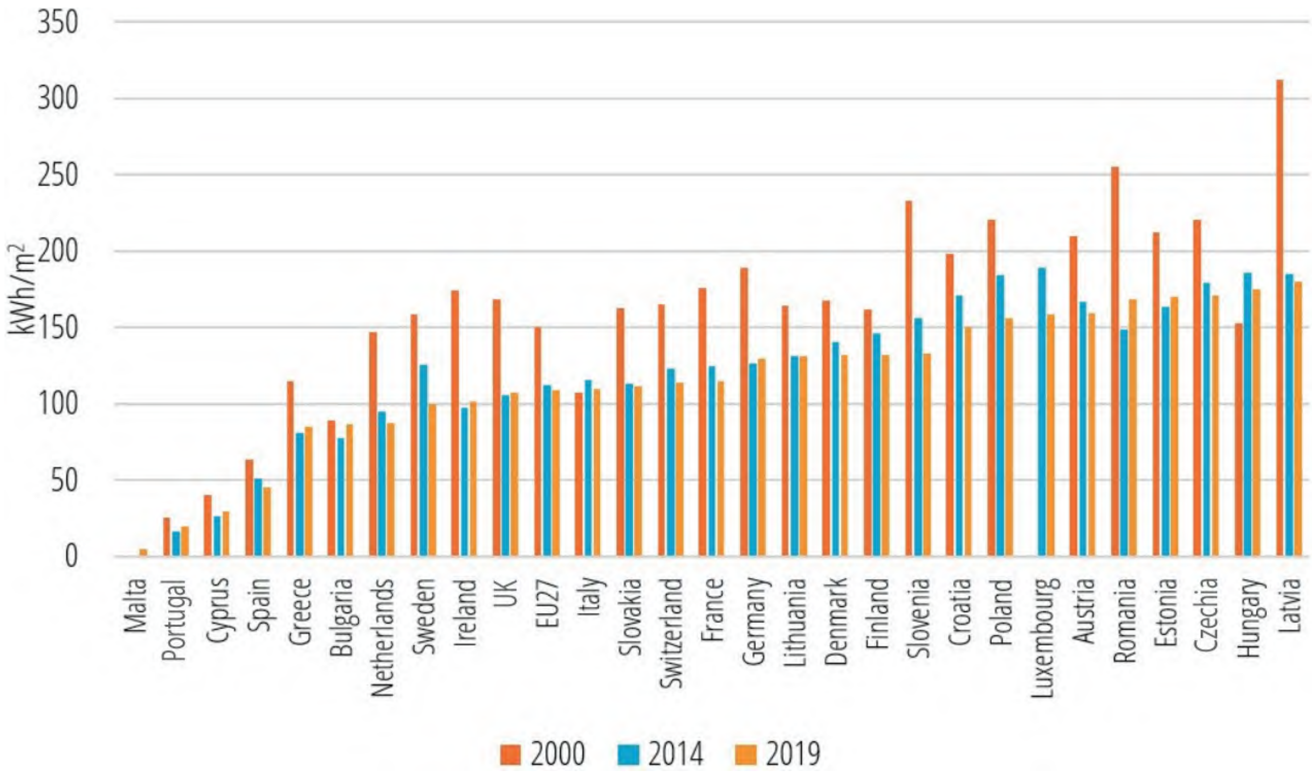


Figure 5.5 Household heating demand ($kWhm^{-2}$) in European countries and the EU. Source: Reproduced with permission from Enerdata (2021).

The energy improvements in the Irish housing stock to date have come from lower cost, more accessible measures such as roof and cavity wall insulation (Ahern and Norton, 2019). Additional energy savings will need to come from more expensive measures such as external wall insulation, internal dry-lining installation and floor insulation, together with low-carbon heating systems (Figure 5.6). Collins and Curtis (2017), from a review of the Better Energy Homes grant, conclude that retrofitting less efficient homes, larger homes and homes with less air circulation provide the best value for money.

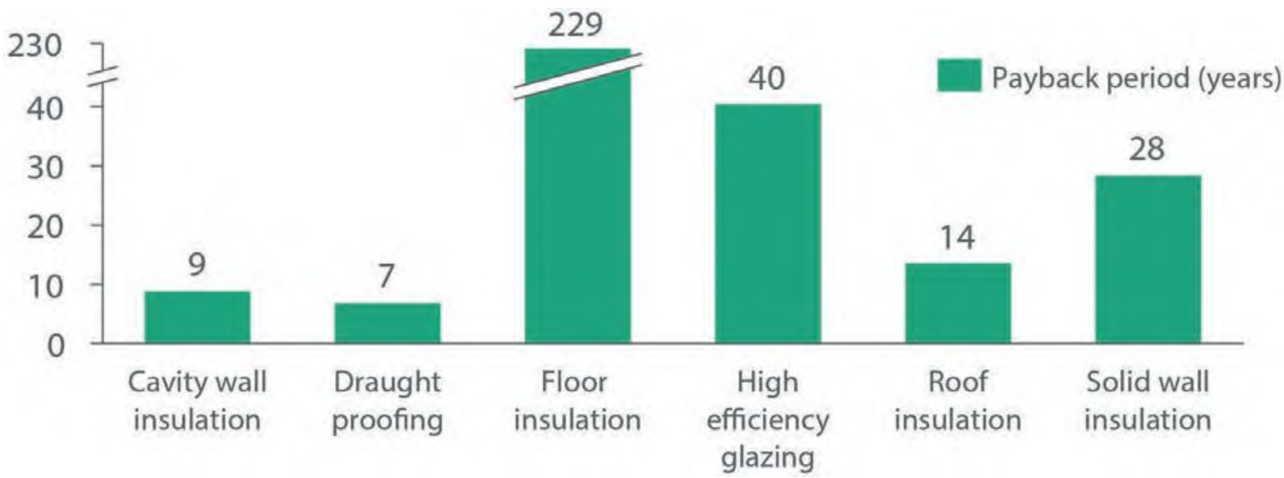


Figure 5.6 Average consumer payback period for fabric measure option in detached, oil-heated dwellings in 2030. Source: SEAI (2022l).

A well-known phenomenon associated with home energy improvements is the rebound effect, which sees energy demand increasing rather than decreasing following measures to improve energy efficiency (Aydin et al., 2017). This is generally explained by the fact that improved insulation means homeowners now actually benefit from heating and thus use it more. For example, in a low-rated house, people would probably just heat the room they are occupying with a fireplace instead of running the central heating. Coyne et al. (2018) found that gas use went up in social housing following retrofits, which provided a great improvement in comfort for the occupants. In another interesting study, based on a sample of 8,572 Irish homes that had undergone works, Coyne and Denny (2021b) found that, on average, a retrofit lowered energy demand by 1,091kWhyr^{-1}. This of course varies with the extent of the measures undertaken and pre-/post-works ratings.

Solid fuel use in secondary heating is a key source of residential emissions (section 3.3.2), which has implications for both air quality and climate. This is generally as a secondary heating source, but there is a large share of households that rely on it for primary heating as well, particularly among those experiencing energy poverty. From a review of stove fuels in Ireland, Trubetskaya et al. (2021) found that torrefied biomass and low-smoke ovoids yield the lowest particulate matter (PM) emissions. Using these fuels as a substitute for smoky coal, peat and wood could reduce PM2.5 emissions by approximately 63% (Trubetskaya et al., 2021).

5.2.1.2 Ireland's targets for improving household energy performance

Ireland published its Long-Term Renovation Strategy (LTRS) in 2020 (Government of Ireland, 2020), and submitted it to the European Commission as required under the Energy Performance of Buildings Directive. It sets the highly ambitious target of retrofitting around 55,000 homes per year from 2023 onwards (Table 5.2).

Year	Heat pumps in residential buildings
2021	13,000
2022	33,500
2023	55,000
2024–2030	56,215 each year

Source: Government of Ireland (2020).

Under the Climate Action Plan 2023 the key targets are:

- retrofitting 500,000 homes to a BER B2 or cost-optimal equivalent standard;

- fitting 400,000 homes with a heat pump.

This will be no easy task; as noted in the Climate Action Plan 2023, it implies "an almost 50-fold increase in annual deep retrofits from 1,500 households retrofitted in 2019 to 75,000 households that will need to be retrofitted in 2030" (Department of the Environment, Climate and Communications, 2022a, p. 53). A study modelling the current uptake rates warns that there will be a significant shortfall, with only 235,000 retrofits (47% of the target) projected to be complete by 2030 (Mac Uidhir et al., 2022).

Heat pumps are technically suitable for 78% of existing residential buildings, and for 66% and 47% of existing commercial and public buildings respectively, without energy efficiency improvements (SEAI, 2022j). For heating, the extraordinary efficiency of the heat pump (250–400%) makes it a much more economical choice than the hydrogen boiler (up to 90%), even before considering the efficiency of the electrolysis process (SEAI, 2020d). Two key barriers to the adoption of heat pumps identified are the need for the house to have good-quality insulation before installation and people's poor understanding of how they operate (SEAI, 2020a).

Despite the considerable benefits to Irish society from improving the energy performance of the housing stock, it has long been established that there are clear reasons why the market fails to deliver it (Clinch and Healy, 2000). A key challenge in retrofitting the poorest performing homes is that these are generally occupied by those who are least able to access the available grants. Recent studies have found an overlap between the homes that need the most work and lower-income households (Buckley et al., 2021a) or an elderly population living alone (McGookin et al., 2022). This points to a need for new, more carefully planned interventions to prevent a situation where energy bills continue to rise for those who are unable to make the move to cheaper alternatives (Gough, 2017).

There have been calls for an area-based approach to retrofitting (Buckley et al., 2021a; Saffari and Beagon, 2022). Dealing with a group of houses with similar characteristics would provide savings from economies of scale. In cities, a neighbourhood approach to retrofits would take advantage of the arrangement of buildings into terraces, which means a row of houses essentially shares an external wall (Buckley et al., 2021b). This approach is supported by SEAI through the Community Grant (previously Better Energy Community) scheme, which provides grants for groups of houses, businesses and community buildings that come together for energy improvement measures (SEAI, 2022h).

5.2.1.3 New builds

Thanks to the Energy Performance of Buildings Directive, every newly built home in Ireland has to meet strict energy standards. Part L of the government guidelines sets out a heat loss value that windows or walls must not exceed. This has been gradually increasing the standard of new builds. While Ireland's 2011 building regulations required an A3 BER rating, this now equates to an A2 rating (Saffari and Beagon, 2022). Since 2020, new builds have to be what is known as 'nearly zero energy buildings' (European Commission, 2021c). This means that any house built after 2020 must be A rated, with most having a heat pump and solar PV in order to meet the requirement for on-site renewables. In addition, the National Planning Framework objective of 'compact growth' aims to ensure that future developments are more densely populated to support district heating and reduced transport demand (Government of Ireland, 2018b). This should ensure that our new homes are future-proofed. However, many studies have raised concerns over the level of non-compliance with building regulations (Dineen and Gallachóir, 2011; Rogan et al., 2012; Ahern and Norton, 2019); see also Volume 3, Chapter 6 for crossover points on overheating, enforcement and regulation).

5.2.2 In our businesses: industry and services

The industry and service sectors are not as well covered as the residential and transport sectors in pathways to deep decarbonisation (Chapter 7). This is primarily because of the limited availability of good-quality, granular data on their energy and emissions (Mac Uidhir et al., 2020a). In December 2018, the Central Statistics Office (CSO) published for the first time the results of the Business Energy Use Survey (BEUS) (Central Statistics Office, 2018). It provides a new basis for the breakdown of energy use in industry and commercial/public services, which was not previously available. SEAI subsequently revised the national energy balances from 1991 to 2018, incorporating these new data (SEAI, 2020e), and has used them as part of a new methodology since the 2020 National Energy Balance (SEAI, 2020b).

5.2.2.1 Industry

In 2021, manufacturing accounted for 37% (c.€148 billion) of Ireland's gross value added (GVA) (Central Statistics Office, 2022a), but only 18% (c.24.3TWh) of energy demand (SEAI, 2022g) and 11.4% of GHG emissions including LULUCF (7.1MtCO_2-eq) (EPA, 2023b)[26]. It is a highly productive sector from an energy and emissions intensity perspective, although this is likely to be skewed by how this economic metric is determined (Annex A.4). By contrast, agriculture (excluding land use) accounted for 1% (c.€4.3 billion) of GVA (Central Statistics Office, 2022a) and 2% (2.7TWh) of energy demand, but 33% of GHG emissions including LULUCF (23.6MtCO_2-eq) (EPA, 2023b). In 2021, the largest manufacturing sectors by share of industrial energy demand were food and beverages (22%), basic metals and fabricated metal products (21%) and pharmaceuticals (20%) (SEAI, 2022g).

There has been a lot of research on the potential for bioenergy in the food and beverage industry (O'Shea et al., 2022b). Within Irish research, the two areas that stand out are dairy processing (Long et al., 2021b; Shi et al., 2021; Logan et al., 2022) and distilleries (Kang et al., 2020; O'Shea et al., 2020; Kang et al., 2021; O'Shea et al., 2021; Kang et al., 2022). Both of these plants are naturally suited to anaerobic digestion, having both organic by-products available and consistent demand for heat. However, for dairy processing this is a lot more challenging, as the majority of emissions are associated with the livestock rather than the processing (Finnegan et al., 2017). Long et al. (2021b) highlight that reducing milk demand by encouraging breastfeeding would provide more emissions savings than renewable gas substitution in milk formula plants.

Ireland has a limited amount of heavy industry, accounting for just 3.5% (2.5MtCO_2-eq) of GHG emissions in 2021 including LULUCF (EPA, 2023b). In 2021, Glynn et al. (2019) assumed up to 50% demand reduction in some energy- and carbon-insensitive industry sectors, such as lime and cement production. This would reflect a move to more sustainable building materials, such as wood (see embodied carbon, section 5.2.4).

5.2.2.2 Commercial services

Similarly to the public sector, the EU Energy Efficiency Directive (2012/27/EU) requires large organisations, public and private, to complete energy audits every 4 years. SEAI has established the Energy Auditing Compliance Scheme to meet this legislative requirement and enable those obligated organisations to report compliance. The SEAI Energy Academy is a new online resource specifically designed for small and medium-sized enterprises. SEAI also runs Excellence in Energy Efficiency Design

[26] Based on thermal emissions from EPA National Inventory Report and 20% of energy industry emissions (EPA, 2022f). Manufacturing accounted for 20% of electricity demand at 500 out of 2,599ktoe in 2021 (SEAI, 2022g).

(EXEED), a programme that supports organisations, both public and private, to improve energy efficiency and embed energy-efficient design thinking that will continue to benefit the organisation. Companies seeking to undergo energy improvements can avail themselves of the accelerated capital allowance (ACA), which allows companies to deduct the full cost of associated equipment from their taxable profits in the same year of purchase.

One key area that has been gaining attention is the projected data centre growth. As outlined in section 4.3, data centres are the main cause of rising electricity demand, which poses a challenge as the grid tries to decarbonise (Deane et al., 2022). Many data centre operators have ambitious targets to achieve net zero emissions or 100% renewable electricity by 2030; however, Ireland's national climate ambition is now framed around carbon budgets, which means that annual and cumulative emissions are important. In November 2021, the Commission for Regulation of Utilities (CRU) published a decision regarding the connection policy for data centres in Ireland, outlining an approach to connection applications that includes assessment criteria encompassing location and the ability to contribute to security of supply. These criteria include constraints on the grid, on-site dispatchable storage and flexibility in demand. Even though some data centre operators may cover 100% of their annual energy demand via renewable power purchase agreements, this does not mean that they are using zero-carbon power at all times of the day, every day of the year. This poses a risk to the emissions ceiling agreed for the electricity sector as part of Ireland's first carbon budget (section 2.4.4). In July 2022, the government released a new statement on the role of data centres in enterprise (Department of Enterprise, Trade and Employment, 2022). It outlines a variety of preferences for prospective development, such as data centre developments associated with strong economic activity and employment that can demonstrate their renewable energy use and demonstrate a clear pathway to decarbonisation and ultimately provide net zero data services.

5.2.3 Public services

There is limited research on the Irish public sector energy and emissions. However, it is a sector that has made good progress thanks to the 2012 EU Energy Efficiency Directive, which encouraged the public sector to lead by example in efforts to improve energy performance and set a target for energy efficiency improvements of 33% by 2020 (European Union, 2012). This introduced the need for a monitoring system to track progress against the energy efficiency targets. Within Ireland, public bodies such as local authorities, government departments and schools must submit their energy data to the monitoring and reporting system maintained by the SEAI (SEAI, 2021e). Compliance with this online energy monitoring and reporting system is very high: approximately 99% of all public bodies and 76% of schools submitted reports in 2020 (SEAI, 2022a).

Public sector buildings over 250m2 must have a display energy certificate to clearly show their energy use and BER. There are supports available under the Public Sector Energy Programme to assist organisations in improving their rating. All public bodies are legally obliged to publish annual statements describing the actions they are taking to improve their energy performance. The public sector exceeded its 33% energy efficiency target for 2020 by being 34% more energy efficient than in 2009 (SEAI, 2022a). The new target for 2030 set in the Climate Action Plan 2021 is a 50% improvement in energy efficiency by 2030 (Department of the Environment, Climate and Communications, 2021b).

5.2.4 Embodied emissions

As illustrated in Figure 5.7, there are three categories of GHG emissions under the widely used GHG Protocol first proposed by Wbcsd (2004).

1. Scope 1 are the emissions from direct fuel use, i.e. burning fossil fuels in an engine or boiler.
2. Scope 2 are the indirect emissions from purchased electricity, i.e. those at the power plant.
3. Scope 3 are the indirect emissions associated with materials or processes, such as the transport of raw goods.

Embodied carbon is the amount of carbon emitted during the construction of a building (Figure 5.8). The extraction of raw materials, the manufacturing and refinement of materials, their transport and installation, and disposal of old supplies can all produce embodied carbon emissions. Essentially, embodied carbon is built into the fabric of a building. The IPCC Special Report on 1.5°C recommended that "new construction to be fossil-free and near-zero energy by 2020" (IPCC, 2018a).

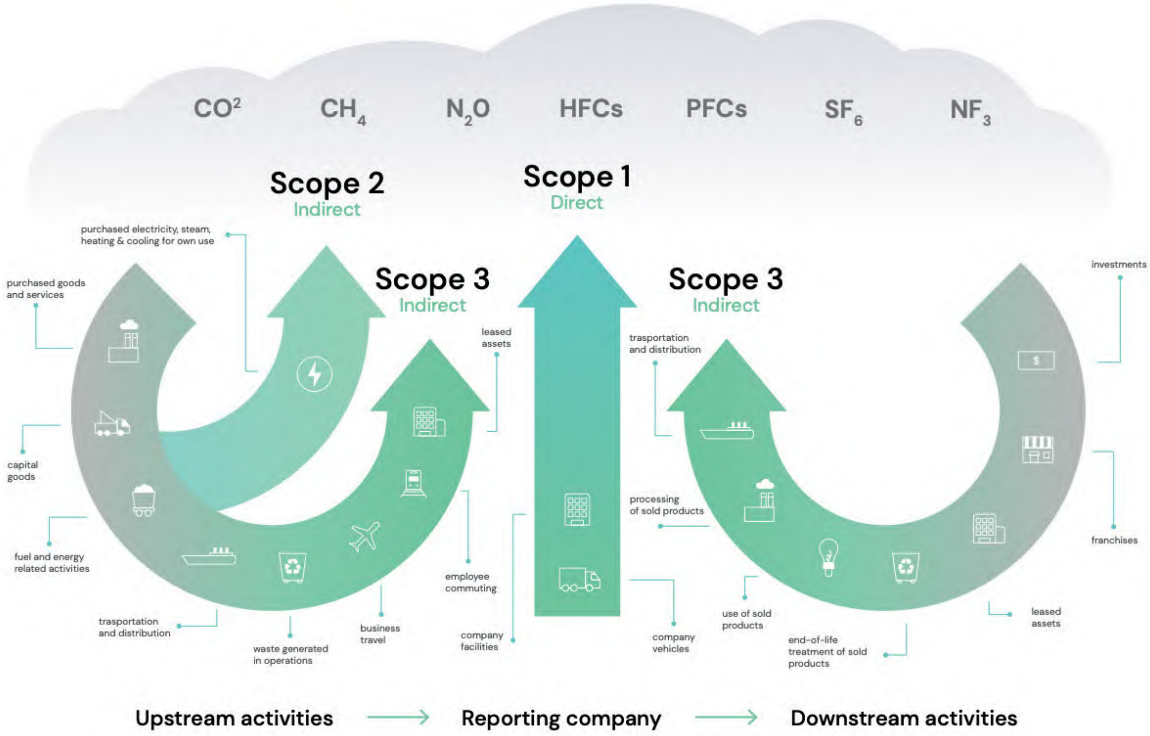


Figure 5.7 What are scopes 1, 2 and 3 emissions? Source: Net0 (2022).

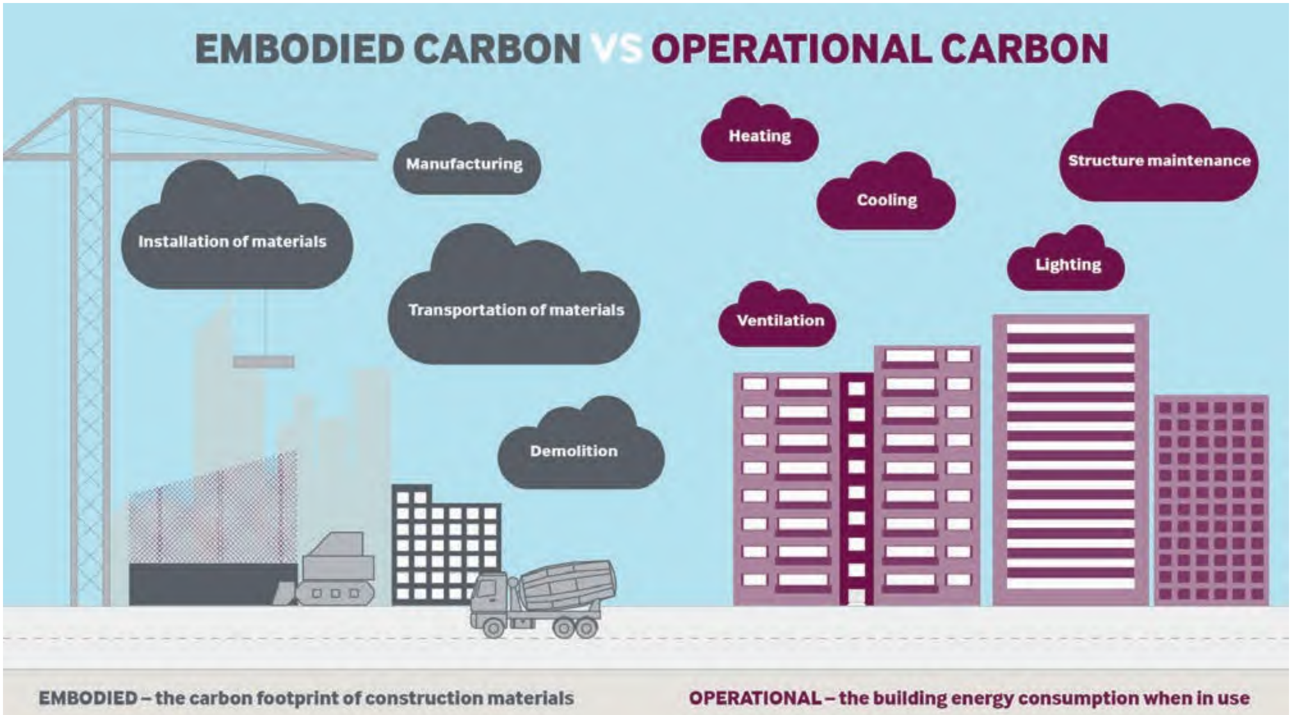


Figure 5.8 Examples of embodied versus operational emissions. Source: Reproduced with permission from RPS Group (2020).

Developing net zero carbon assets requires driving down embodied carbon to an absolute minimum. As companies commit to net zero pathways for their own emissions, they are now focusing on reducing the carbon footprint of what they build. Less embodied carbon will mean a lower requirement for carbon sequestration. This is a vital step in reaching global emission reduction targets. As buildings become more energy efficient, the embodied energy of the materials makes up a greater share of the life cycle emissions (Goggins et al., 2016).

With the introduction of the revised nearly zero energy buildings standard through Part L of the Building Regulations 2019 for both residential and non-residential buildings, the upfront embodied carbon now represents a much greater part of the whole life cycle carbon of the building. A review of EU buildings found that the average share of embodied GHG emissions rose to 45–50% for highly energy-efficient buildings from approximately 20–25% of life cycle GHG emissions in older buildings (Röck et al., 2020). With the move to zero emissions construction, the embodied emissions are as high as 90% of life cycle GHG emissions.

The vast majority of embodied emissions come from cement. During the cement manufacturing process, CO_2 is produced during the production of clinker. Clinker is produced when limestone, mainly calcium carbonate ($CaCO_3$) and small amounts of magnesium carbonate ($MgCO_3$), undergo calcination at high temperature to produce lime (calcium oxide (CaO) and magnesium oxide (MgO)) and CO_2. The activated lime that results from this process combines with silica and alumina in the kiln feed to form cement clinker. Until the year 2000, one company operated two cement plants in Ireland. A second company opened a new cement plant in 2000 and a third cement producer entered the market in 2003, bringing the total number of plants to four. Process emissions of CO_2 from cement production declined between 2007 and 2011 as a result of the economic downturn. However, emissions have increased since 2012, in line with post-recession economic growth (EPA, 2022e). Habert et al. (2020) provide a review of options to decarbonise cement manufacturing. However, within Ireland there has been no research to date.

Retrofitting older buildings is an important means of reducing the demand for cement while also supporting town revitalisation and safeguarding cultural heritage.

6

Agriculture, Forestry and Land Use

Key messages

Ireland's agricultural sector must deliver significant emission reductions to meet climate targets and mitigate its effects on biodiversity, water and air quality.

Innovations in the development of feed additives to inhibit enteric methane protection are under way and the use of protected urea to reduce nitrous oxide emissions is still in the early stages of implementation.

Optimal use of no-regret livestock management measures, such as increasing the dairy Economic Breeding Index, improving herd genetics, improving animal health and promoting efficient feeding strategies, will help in reducing greenhouse gas emissions.

Diversification within the sector will be necessary to achieve deep emission reductions. It is very important because this can reduce livestock numbers and enable different land use strategies, such as bioenergy and agroforestry.

Land use, land use change and forestry (LULUCF) is a net source in Ireland. An integrated approach of land management is urgently required to avoid trade-offs between climate actions, biodiversity, water quality and food production.

Different combinations of afforestation, rewetting of organic soils and enhancing carbon sequestration in mineral soils are the primary means of achieving net zero emissions within LULUCF.

Additional analysis of drainage and the nutrient status of peat soils (including agricultural and forested land) would help in understanding the total potential of reduced emissions and increased removals that could be achieved through land management.

6.1 Agriculture

Agriculture has a key role in delivering our national objectives by protecting both our climate and environmental credentials. Agriculture is the largest sectoral contributor to GHG emissions in Ireland (section 2.3), at 38% (exclusive of LULUCF) of the national total in 2021. It is responsible for the majority of CH_4 emissions, from livestock, and the majority of N_2O from manure and nitrogen fertiliser applications. From an air quality perspective the sector is almost exclusively responsible for all ammonia emissions. The Climate Action Plan 2021 (Department of the Environment, Climate and Communications, 2021b) outlines the targets necessary to achieve agricultural emission reductions from 23 $MtCO_2$-eq to 16–18$MtCO_2$-eq by 2030. *Ag Climatise* – A Roadmap Towards Climate Neutrality (Department of Agriculture, Food and the Marine, 2020b) envisages Irish agriculture to be carbon neutral by 2050. The roadmap is focused on stabilising CH_4 emissions (reductions in CH_4 of 24–47% by 2050) and a significant reduction in fertiliser-related N_2O emissions (up to 50%). Figure 6.1 summarises the total GHG emissions from the agricultural sector between 1990 and 2021 (EPA, 2023c).

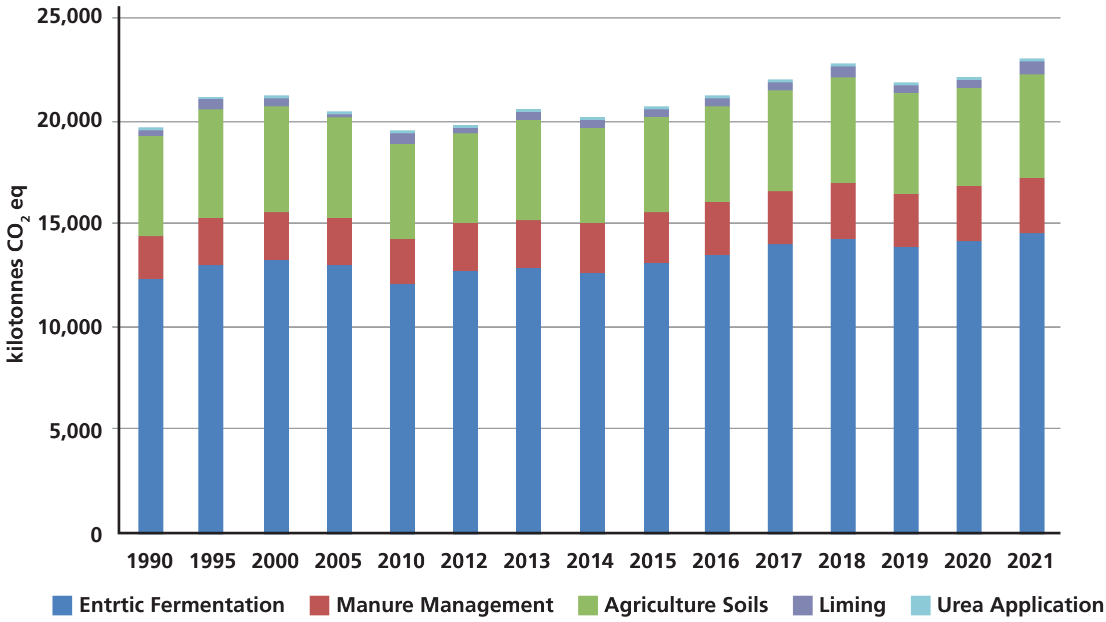


Figure 6.1 Estimates of emissions across the agricultural sector, 1990–2021. Source: EPA (2023c).

National GHG inventories point to the significance of the livestock population in driving emissions, accounting for over 90% of CH_4 emissions from agriculture. In 2021 the sector's emissions increased by 3.1% from 2020 levels. The increases in the use of nitrogen fertiliser (5.2%) and liming (49.5%) increase in dairy stock numbers (2.8%) and milk production (5.5%) have all contributed to this figure. As discussed in section 6.1.1.1 the structure of the herd is important, as beef and dairy systems have markedly different emissions profiles. Irish agriculture is concentrated on dairy and beef. Unlike energy industries or transport, where CO_2 from the combustion of fossil fuels is the dominant GHG, the bulk of agricultural emissions are associated with CH_4 (enteric fermentation and manure) and N_2O (mainly slurry and artificial fertilisers). Enteric fermentation alone accounts for 20% of GHG emissions (12.1Mt in 2019), more than all emissions from road transport, for example. Agriculture, fisheries, and forestry accounted for 1.2% of GVA in the Irish economy in 2017 (Central Statistics Office, 2021b).

6.1.1 Mitigation

Over the last number of years, Teagasc has developed solutions to enhance reductions in emissions from the Irish agricultural sector. The mitigation actions prescribed have mainly focused on measures such as the dairy Economic Breeding Index (EBI), beef genomics and the extension of grazing seasons (Teagasc, 2018). The Climate Action Plan (2021) outlines several guidelines for the agricultural sector within the themes of improving carbon efficiency of production, reducing nitrogen use and adopting technical guidelines, as prescribed by the Teagasc marginal abatement cost curve (MACC) (Teagasc, 2018; Department of Communications, Climate Action and Environment, 2019). The challenges of agricultural mitigation include the slow rate of uptake, cost of equipment, knowledge transfer and enabling the market, along with the wide array of barriers faced by farmers and land managers. Figure 6.2 illustrates the MACC for agriculture for 2021–2030 for CH_4 and N_2O abatements. CH_4 reduction solutions are focused on animal genetics for increasing animal productivity, optimising finishing times and changing the dietary measures of the animals. For nitrogen reductions, strategies such as use of clover, low-emission slurry spreading and manure additives, and improving liming were recommended. The analysis shows that the application of the dairy EBI (improving the genetic merit of the dairy herd) and changes in fertiliser types (e.g. protected urea) offer the largest mitigation potential to 2030.

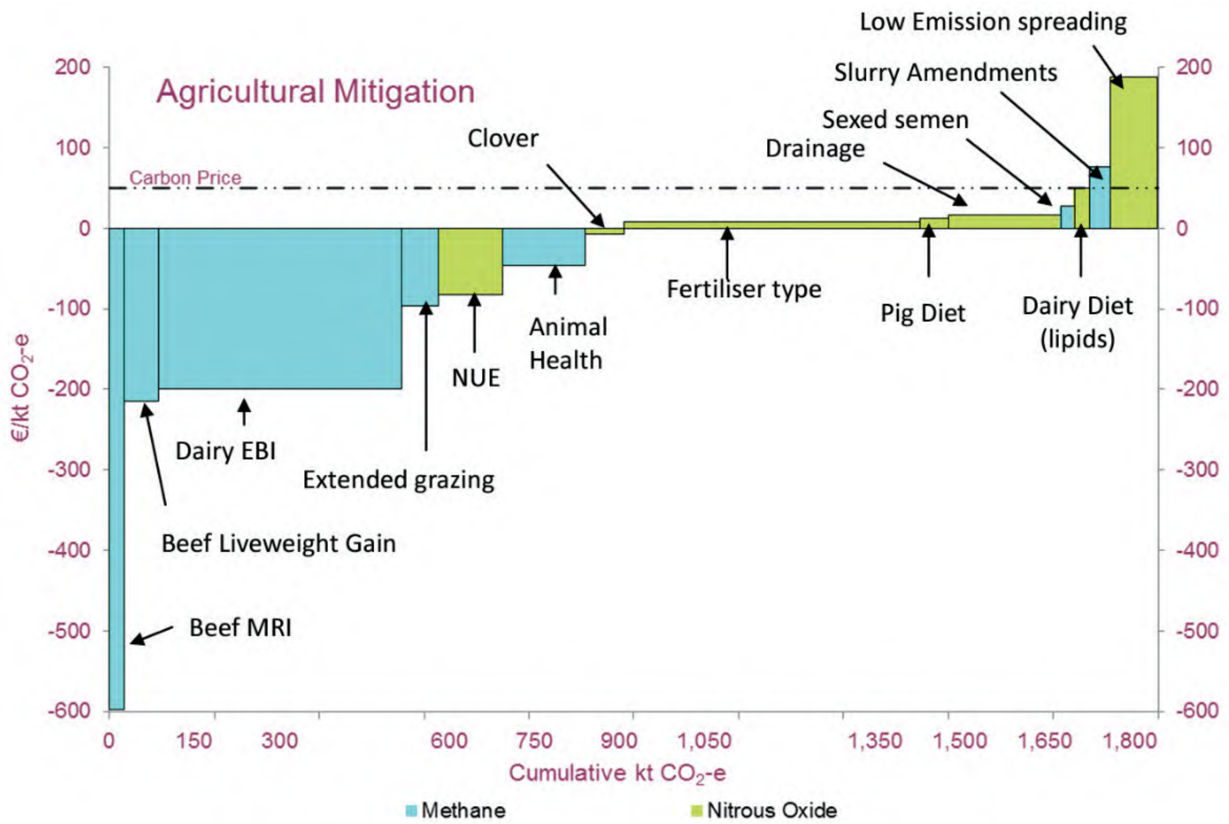


Figure 6.2 Marginal abatement cost curve for agriculture for 2021–2030 (CH_4 and N_2O). MRI, Maternal Replacement Index; NUE, nitrogen use efficiency. Source: Buckley et al. (2020).

6.1.1.1 Emissions from enteric fermentation

Emissions from cattle, sheep, swine and other livestock are the four major contributors to enteric emissions in Ireland, with CH_4 emissions from cattle accounting for more than 60% of the total agricultural emissions in 2021 (EPA, 2023a).

Figure 6.3 summarises the total CH_4 emissions from livestock between 1990 and 2019. In recent years, especially since 2015, dairy cattle emissions have shown an increasing trend; this is mostly due to the lifting of the milk quota. Overall increments in emissions post 2013 from non-dairy cattle were noted until 2018; this was due to increases in sales of beef aimed at export markets. However, a dip in emissions was noted for 2019; this was due to Brexit, COVID-19 and a trend for farmers to switch to dairy farming. In Irish agriculture, the dairy sector is the dominant sector in terms of contributing to total agricultural GHG emissions. The total cattle number in Ireland in 1990 was 7,571,300; this compares with the 2021 figure of 7,358,900 (Central Statistics Office, 2021b), constituting a reduction of 2.8% over the period. The dairy cow numbers for 2021 (up to 1 June) stood at a total of 1,603,721 (a rise from 1.4 million in 2017). Dairying is the most profitable of Ireland's mainstream agricultural enterprises (ICBF, 2021).

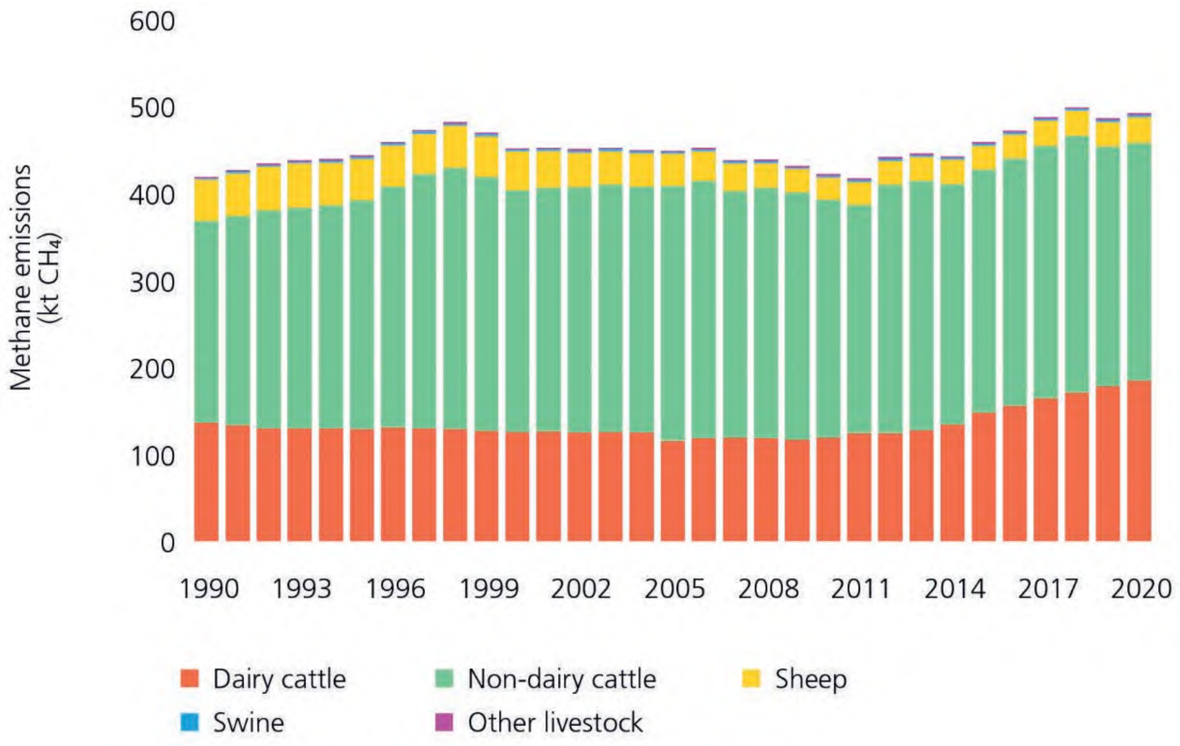


Figure 6.3 CH_4 emissions from livestock in Ireland between 1990 and 2020. Source: Climate Change Advisory Council (2021).

Several recent studies have discussed the potential of adopting innovative breeding strategies to mitigate CH_4 emissions from the agricultural sector. This research is still at an early stage, as it is necessary to develop phenotypes that can be used by farmers to mitigate CH_4 emissions as well as optimise production at farm level (de Haas, 2017; González-Recio, 2020). RumenPredict is an EU-funded project aimed at generating the necessary data to predict how host genetics, feed additives or microbiome can affect emission phenotypes, and at developing genetic/diet/prediction technologies further to increase efficiency while decreasing the environmental impacts of ruminants (RumenPredict, 2020). Inclusion of multi-species swards for feeding cattle is a sustainable method for mitigating enteric fermentation in cattle; Montoya-Flores et al. (2020) reported that cattle fed a diet with a high proportion of legumes led to a reduction of 20% in CH_4 emissions and subsequently increased nutrients in the soil. Incorporation of white clover into cattle diets was reported to be beneficial, with increased milk yield/solids and lower levels of CH_4 output. However, several studies have also shown clover use to increase N_2O emissions as well increase deaths from bloat in cattle; hence, proper management/handling of feeding in this regard is mandatory (Conaghan and Clavin, 2017; Scully et al., 2021). Trials of feed additives such as pressed oil, seaweed extracts, halides and 3-nitrooxypropanol have all been reported to show improved cattle health and reduced CH_4 emissions (Waters, 2021). It has also been recommended that slaughtering beef animals at a younger age would help to reduce the volume of CH_4 produced over the animal's lifetime (Department of Communications, Climate Action and Environment, 2019). 'Meth-Abate', a project funded by the Department of Agriculture, Forestry and the Marine (DAFM), aims to reduce CH_4 emissions from ruminants and stored slurry by using anti-methanogenic feed additives (Teagasc, 2022). Several varieties of tropical seaweed, oils, plant extracts, seaweed extracts and halides were used in the analysis. A two-thirds (67%) reduction in CH_4 emissions was observed when tropical seaweed (*Asparagopsis taxiformis*) was used. This compares with a 20% reduction using oils and an 18% reduction using plant extracts. Similar results were observed when halide-based extracts were shown to reduce emissions by 50–80% in beef cattle (Hegarty, 2021).

Recently the European Food Safety Authority (EFSA) authorised 3-nitrooxypropanol as a feed additive for ruminants; the above stated active ingredient suppresses the enzyme that triggers CH_4 production in the animal stomach. According to EFSA, 3-nitrooxypropanol is efficacious in reducing CH_4 emissions by cows in milk production, and an average reduction in CH_4 of 25.7% can be achieved by using this additive (Alemu et al., 2021). In Ireland, Teagasc is presently working on demonstration projects to validate these claims (Waters, 2021). A recent study on multi-species swards also showed increased milk production when swards were zero grazed but harvested and fed to indoor dairy cows; this alternative practice can help in maintaining milk production while also reducing nitrogen fertiliser use in grazing systems (McCarthy et al., 2021). However, in zero-grazed pastures a full life cycle analysis needs to be conducted to account for the energy costs of harvesting and housing animals in order to establish any sort of emission benefits. The total carbon footprint of pasture-based dairying cows/milk in Ireland is comparatively lower than in other countries, at 0.99kg CO_2 per kilo of fat and protein-corrected milk compared with the global average of 2.4kg (O'Brien et al., 2015). A study by Finnegan et al. (2017) highlights the GWP of different dairy products in Ireland. The results show that a litre of liquid milk produces emissions of 1.589kg CO_2 per kilogram of fat- and protein-corrected milk, and that figure increases for various processed milk products. It is also worth noting that raw milk production pre-processing accounted for between 80% and 97% of the total emissions created. Pre-farm gate policies in developing circular approaches and using native feed alternatives could be a viable mitigation action within this sector.

6.1.1.2 Other greenhouse gas emissions in agriculture

Emissions of N_2O from the agricultural sector follow similar trends to those of CH_4 because cattle also largely determine the amount of nitrogen inputs to agricultural soils from synthetic fertiliser and animal manures, which combined produce the bulk of N_2O emissions (92% of total N_2O emissions in 2019).

The CAP Strategic Plan for 2023–2027 (Department of Agriculture, Food and the Marine, 2022b) has outlined a funding scheme (€35 million) for farmers, promoting diversification into protein crops. Protein crops can serve as a very valuable break crop in tillage crop rotations, and they provide an essential protein source for animal feed for free, while leguminous crops also help in nitrogen fixing and thereby reduce the use of chemical fertiliser. *Ag Climatise* recommends the use of stabilised or treated urea to reduce ammonia and GHG emissions, and, by the end of 2023, Ireland will adopt the use of stabilised urea for fertilising agricultural fields (Department of Agriculture, Food and the Marine, 2020b). Stabilised urea has the potential to reduce N_2O emissions by 71% compared with calcium ammonium nitrate (CAN) fertiliser, and there are also reductions in ammonia emissions of 79% compared with traditional urea application (Forrestal et al., 2018).

Legumes, including clovers, can provide nitrogen to a sward through a symbiotic relationship with rhizobium bacteria, which fixes atmospheric nitrogen into plant-utilisable forms. Increased use of multi-species swards in managed grasslands was shown to lower N_2O emissions by 41% compared with a perennial ryegrass monoculture (Cummins, 2021). This method could be widely adopted to contribute towards sustainable grassland production with enhanced carbon sequestration. The results from SMARTSWARD, a project aimed at achieving a sustainable pasture-based beef production system, showed that multi-species swards grow under reduced nitrogen inputs ($90kgNha^{-1}yr^{-1}$), in contrast to ryegrass monocultures, which receive $250kgNha^{-1}yr^{-1}$ (Gilsenan, 2019). Multi-species swards have climate adaptation co-benefits as well, as studies have found them to have increased drought tolerance (Dumont et al., 2022). Studies have also shown the use of legumes and herbs, along with grasses, on grazing-focused dairy farms to increase pasture production across various nitrogen application levels (Hearn et al., 2022).

The demonstration project Biorefinery Glas looked at the use of biorefining fresh grass into a range of new products and improving protein and nutrient use efficiency for cattle fields, and using waste by-products as a suitable fertiliser to curb nitrogen emissions in Ireland (EIP-Agri, n.d.). U-Protein (Unlocking Protein Resource Opportunities to Evolve Ireland's Nutrition)[27] is a multi-disciplinary project within Ireland that focuses on exploring sustainable crop- and marine-based protein alternatives for Ireland. As well as contributing to nutrition in the food sector, the project also aims to valorise bioactive compounds from residual streams into bioactive novel compounds.

Ammonia emissions in Ireland originate mainly from the agricultural sector (99.2%) (Buckley et al., 2020). Approximately 89.4% of these emissions is from manure use in soils and the remaining 10.6% is from the use of synthetic fertilisers and transport. Mitigation in this regard is a complex process, as 60% of cattle are on pasture-based systems and nitrogen excreted is thus hard to quantify, making it challenging to achieve ammonia abatement. Teagasc's MACC report suggests the introduction of low-protein feeds in dairy; the use of slurry amendments and acidifiers in storage; and improvements to nutrient management systems via the application of liming and clover (Teagasc, 2018).

6.1.1.3 Energy in agriculture

Emissions from energy related to fuel combustion within the agricultural sector are small, at 3% of total agricultural emissions. Machinery is likely to be reliant on liquid fuels or gaseous fuels for the foreseeable future. Seasonality (very little use over the winter, intense demand during harvesting) means that electrification would be complex and incompatible with current practices (the use of contractors). A cooperative hydrogen refuelling infrastructure may provide a means of decarbonising more year-round agricultural activities, where multiple adjacent farms utilise an electrolyser/dispenser for economy of scale, providing local flexible demand, and potentially receiving a payment (Janke et al., 2020). Work by Upton et al. (2013) investigated energy consumption on 22 dairy farms in Ireland, and, overall, a total of 31.73MJ was required to produce 1kg of milk solids, of which 20% was direct and 80% was indirect energy use. Electricity accounted for 60% of the direct energy use, and was mainly used in milk cooling (31%), water heating (23%) and milking (20%). Imports of high-protein feed materials into Ireland are responsible for significant emissions (which are largely not accounted for), and several actions by the government have been aimed at promoting the production of protein crops in Ireland, as mentioned in section 6.1.1.

[27] https://u-protein.ie/

6.2 Forestry

In Ireland, forested land refers to all the public and private plantation forests and is defined as an area of land in which the tree crown has grown to more than 20% of the total occupied space. As of 2022, around 808,848ha of Irish land is considered to be forested land (Department of Agriculture, Food and the Marine, 2023). Forested land acts as a net emission remover, where CO_2 is sequestered by trees at a rate dependent on their species and age. However, low forest planting rates in recent years are a future risk in terms of our national forest estate continuing to act as a significant carbon sink. This is evident from Figure 6.4, which illustrates the historical trends in CO_2 emissions from forestry in Ireland. Sequestration rates from the year 2000 have increased significantly, especially in areas of forest land converted from grasslands and forest land converted from wetlands. However, in 2021 the forestry sector was almost at the point of turning from a sink into a source. This is concerning given the fact that harvesting has significantly increased from 1.7 million m^3 in 1990 to 4.3 million m^3 in 2023 (Department of Agriculture, Food and the Marine, 2020a). The high planting rates in the 1990s (see Figure 6.4) took place to a large extent on organic soils, but recent changes in emission factors for forestry on peat soils means that planting will need to focus on mineral soils with lower organic content, therefore creating further challenges for increasing planting rates. This reduces the area of land in Ireland suitable for forestry planting (EPA, 2022e). High rates of planting in the 1990s mean that much of those lands are already harvested. The land will be replanted but it takes time for the mitigation potential to ramp up as the trees grow.

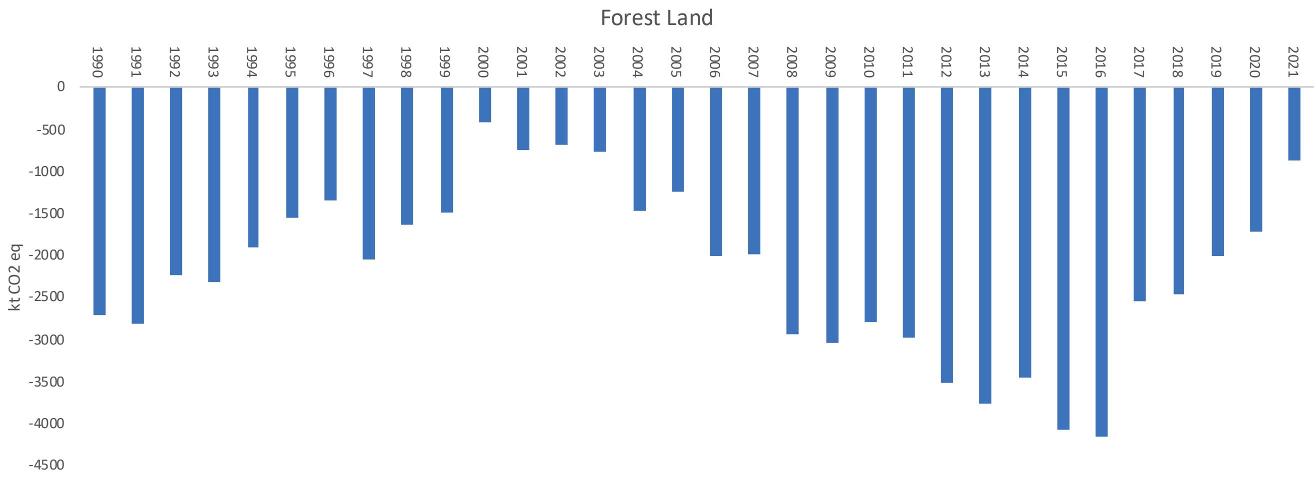


Figure 6.4 Trends in CO_2 emissions from forestry (1990–2021). Source: EPA (2021a).

6.2.1 Mitigation

Forestry in Ireland operates within a legal and regulatory framework; this enables the protection of forests and ensures that forestry operations and activities are carried out in compliance with the principles of sustainable forest management. The Minister for Agriculture, Food and the Marine provides authority under the Forestry Act 2014 to fell or otherwise remove a tree or trees and to thin a forest for silvicultural reasons. With the protection of forests being of paramount importance, controlling drivers of deforestation (subsistence agriculture, mining and urban expansion) and forest degradation (wildfires, overharvesting, pest outbreak, etc.) needs to be properly governed and sufficiently funded (IPCC, 2022b). The proportion of forest area across the EU is 38%, while it is 11% in Ireland. Like Ireland, Denmark and the Netherlands are also net LULUCF emitters and both countries have low forest cover and a large proportion of exploited peat soils (Eurostat, 2018). From the EPA's 2021 estimation of emissions, the declining potential of Ireland's forestry sector to act as a sink is mostly because of the age profile of trees (Department of Agriculture Food and the Marine, 2022c) and declining afforestation rates. Several delays in licensing for felling and planting schemes have also led to delays in achieving targets in the forestry sector (Teagasc, 2021).

The forestry sector is undergoing change and adapting more to its role as an ecosystem services provider through continuous cover forestry (as opposed to clear felling) (Department of Communications, Climate Action and Environment, 2019, greater use of native and broadleaved species, biodiversity and recreation. The Climate Action Plan 2021 also highlights the launch of a new forestry programme in 2023 focusing on a climate-smart forestry strategy for Ireland (Department of the Environment, Climate and Communications, 2021b). The report also recommends new forest management systems with the use of decision support tools to help make decisions on the timing of harvesting (such as extended rotations), which will optimise carbon storage within Irish forests. As well as the economic benefits, there is an environmental return from both afforestation and agriculture. As a tree grows, CO_2 is sequestered in the live wood both above and below ground. On decomposition, needle/leaf and forest floor litter also contribute to carbon stored in soils. On thinning or final harvest, carbon is removed from the forest as roundwood for processing. However, there are also losses to the atmosphere, as carbon in wood products is stored until the products eventually decompose, are burnt, wood for energy is combusted or unharvested biomass (e.g. logs, branches, roots) decomposes, releasing carbon to the atmosphere. In addition, different harvesting and thinning regimes can impact total forest carbon, which includes both forest carbon and carbon in harvested wood products. It must be also be noted that living systems are susceptible to changes; hence, proper management techniques are of paramount importance (Duffy et al., 2020b; O'Donoghue and Ryan, 2020)

6.2.1.1 Afforestation

Ireland's national afforestation is falling short of targets (despite considerable afforestation subsidies); however, there is a growing policy interest in increasing afforestation to optimise carbon sequestration (Kanowski, 2010) and mitigate the relatively high share of GHGs generated by the agricultural sector. Afforestation is an ideal pathway to enhance climate resilience and biodiversity and provide a variety of beneficial ecosystem services. Afforestation is increasingly valued for its potential to enhance ecosystem services and is being actively promoted in many countries through state policy and support (Upton et al., 2014). Forest cover expansion is included as a source of CO_2 emission reduction under the Kyoto Protocol, which is a significant factor in the promotion of forest expansion policies. Within Europe, Ireland possesses one of the lowest areas of forest cover, at approximately 11% of the total land use. This is much lower than the ambitious goal of achieving an increase in forest cover to 17% by the year 2030 (Department of Agriculture, Food and the Marine, 2022c). In spite of Ireland's public support and valuing afforestation greatly, farmers have been reluctant to plant forestry due to a range of factors, including non-pecuniary costs related to changes in land use and lifestyle (Upton et al., 2014; Vafeas, 2021).

It is evident that Ireland's path towards climate neutrality will require significant afforestation strategies along with integrated mitigation from agriculture and other land use sectors (elaborated in Annex A.3.4). Figure 6.5, from a land balance model developed by Duffy et al. (2022b), summarises various scenario models (elaborated in section 7.2) aimed at achieving climate neutrality within the agriculture, forestry and other land use (AFOLU) sector, with projections up to the year 2120. Among the six scenarios (0–5) modelled by the authors, all except scenario 4 accounted for afforestation (until the year 2050) as a mitigation strategy. Scenarios 2, 3 and 5 accounted for afforestation rates of 35,785; 26,086; and 24,299hayr^{-1}, respectively, noted in the peaks shown for sequestered carbon in these scenarios. The present *Ag Climatise* roadmap for Ireland proposes to have afforestation rates of up to 8,000hayr^{-1} (Department of Agriculture, Food and the Marine, 2020b).

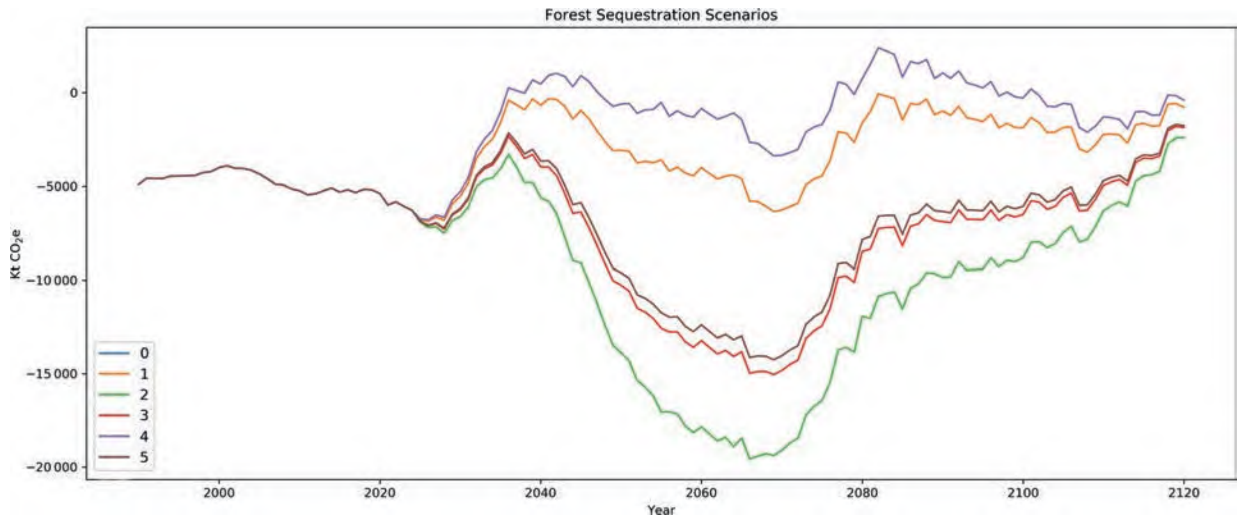


Figure 6.5 Net marginal GHG flux (accounted for as net zero CO_2 balance) from forestry, 1990–2120. Source: Duffy et al. (2022b). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/)

When peatlands are drained for the establishment of new forests, CH_4 emissions cease but CO_2 emissions increase substantially, due to the creation of aerobic conditions and oxidation of organic matter. These processes are partially offset by the uptake of CO_2 by the growth of vegetation and the accumulation of carbon in woody tissue and litter on the forest floor (Black, 2010). Hence, afforestation protocols with a focus on sustainability and avoiding such negative impacts need to consider soil carbon, water quality, biodiversity and society more generally. Afforestation in Ireland needs to focus on tree planting on 'marginal grassland' soils and in 'marginal farming systems' (Farrelly, 2015). DAFM recently introduced (from January 2023) the Agri-Climate Rural Environment Scheme (ACRES), which is a farmer-centric programme to help address biodiversity decline while delivering income support for up to 50,000 farms in Ireland. This scheme is the successor to the Green, Low-Carbon Agri-Environment scheme (GLAS) and entails two schemes, namely ACRES Co-operation and ACRES General. Designated ACRES advisers will help farmers to design and adopt a farm sustainability plan, and the payments made will be results based. ACRES has been designed to deliver significant long-term environmental improvement through the participation of a significant number of farmers on the most appropriate land, with each making a strong improvement on their farms (Muldowney, 2022).

6.2.1.2 Agroforestry

In Ireland, agroforestry, also known as silvopastoral agroforestry, involves the practice of combining forestry and agriculture in mutually beneficial ways. The IPCC Special Report on climate change and land, published in 2019 (IPCC, 2022d), identified agroforestry as a sustainable practice to leverage climate change mitigation and adaptation, increase food security, combat soil erosion and increase carbon sequestration. Ireland's National Biodiversity Action Plan 2017–2021 (Department of Culture, Heritage and the Gaeltacht, 2020) has been at the forefront of promoting agroforestry within the farming sector.

The combination of forestry and crop or livestock farming enables landowners to diversify their stock and expand their economic stability. Another reason for the revived interest in agroforestry is as a method of tackling climate change and sequestering carbon emissions and GHGs. Teagasc, in collaboration with the Forestry Division of DAFM, has a grant scheme in place to promote agroforestry among farmers. The GPC 11 grant covers most of the costs associated with planting and maintenance; the rate of funding varies based on the type of planting used. Several good examples of agroforestry promotion can be found in eastern European countries, where it was introduced to reduce the effect of extreme events such as winds and flooding at the beginning and in the middle of the last century (Santiago-Freijanes et al., 2018).

In Ireland, current agroforestry rates are much lower than the European average (Irwin, 2021). The willingness of farmers to practise agroforesty has been much lower than expected despite profitable financial incentives currently in place to promote agroforestry uptake. A study by Teagasc and University College Dublin analysed this issue, and the findings showed that the current method of increasing agroforestry uptake, which is mainly top-down driven and focused on the economic incentives currently in place, will not suffice to increase tree cover on Irish farms. The recommendation from this study focuses on encouraging people with influential status within the farming community to promote agroforestry by promoting co-design and a co-creative synergistic system (Irwin et al., 2022).

6.3 Land use and land use change

Land use, land use change through time and natural land cover are all linked to the climate system through the carbon, hydrological and nutrient cycles that underpin the functioning of terrestrial ecosystems (Chapin et al., 2002). Land use is a crucial climate mitigation measure available to Ireland, but there are significant challenges to be overcome to maximise the potential contribution from land use. The LULUCF sector considers the influence of human interventions and management on the complex biophysical systems of land and vegetation that lead to both emissions and removals of GHGs. Emissions and removals are reported across five land use categories: forest management, cropland, grasslands, wetlands, and settlements and other land (Climate Change Advisory Council, 2021). Management practices on agricultural grassland and managed peatland are the major net sources of emissions in Ireland. Unlike in most EU countries, land use in Ireland is a net emitter of GHGs. This is because Ireland has (1) a relatively small land area under forestry and (2) a large area of peat soils that have been exploited for energy production, forestry or agriculture.

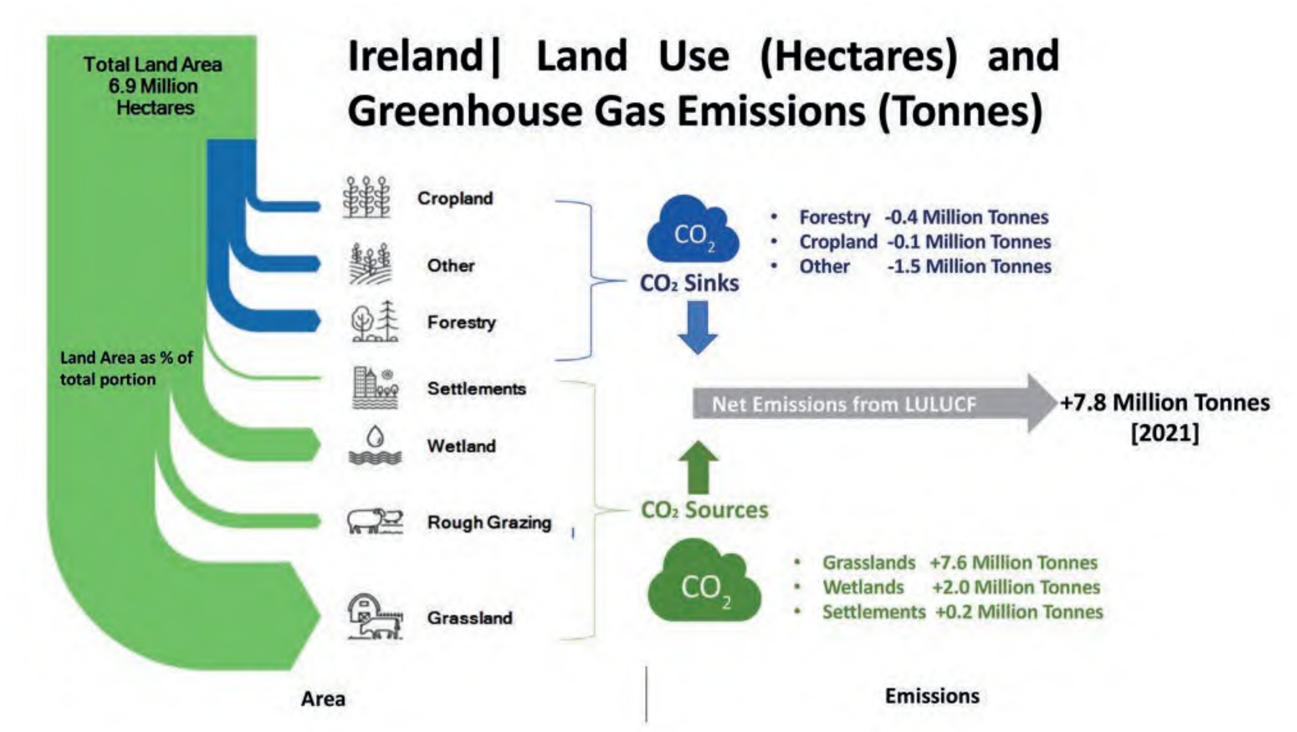


Figure 6.6 Land use and GHG emissions generated from the LULUCF sector in 2021.

The LULUCF sector in Ireland is a significant net emitter of GHGs, as illustrated in Figure 6.6. Removals of emissions are predominantly from forested land, and emissions from other sectors should be mitigated to ensure the LULUCF sector's function as a carbon sink. In Ireland, the restoration of peatlands and organic agricultural soils represents a window of opportunity to mitigate emissions. Although not sector specific, grasslands account for 59.2% of total land use in Ireland (2020 figure). Grasslands present in mineral soils absorb and release CO_2, emit CH_4 from grazing livestock and emit N_2O from soils. This is not the case with grasslands on organic soils, which are net emitters of carbon and will have to be managed or rewetted in future (Haughey, 2021). Recent research by Madigan et al. (2022) indicates that most Irish grassland soils are close to saturation, although the authors postulate that one-off full inversion tillage of carbon-rich topsoil down to 30cm depth during grassland re-seeding could result in CDR of approximately $3.7–7.3tCO_2\text{-eq}ha^{-1}yr^{-1}$ for a period of at least 20 years. Figure 6.7 shows the emissions from the LULUCF sector which mainly come from pasture-based farming and wetlands (land use change-associated activities), and also from grassland and forested land on wetland soils.

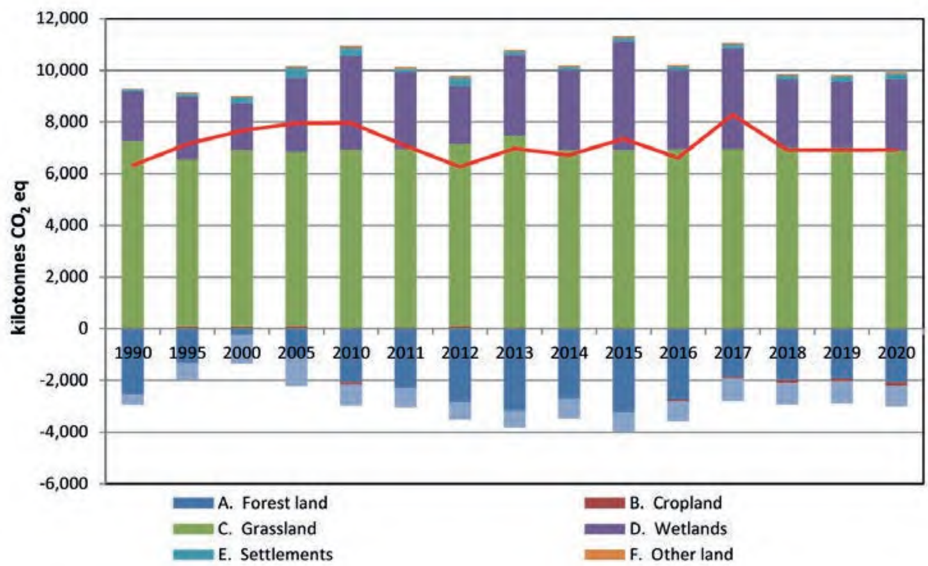


Figure 6.7 Historical emissions and removals from the LULUCF sector in Ireland. Source: EPA (2021).

Cultivating energy crops can result in synergies or trade-offs between GHG emission reductions and other sustainability effects, depending on context-specific conditions (Vera et al., 2022). Despite potentially providing GHG mitigation benefits, the production of dedicated energy crops could worsen other aspects of sustainability when not considering context-specific conditions, e.g. increased food prices driven by land use change (Haughey, 2021). The integrated approach of focusing on mitigation activities such as land management for bioenergy has the potential to contribute towards climate change mitigation (Mbow et al., 2017).

When executed on a large scale, bioenergy and BECCS have been assessed as having significant potential to contribute to global mitigation efforts. Negative impacts of the large-scale deployment of bioenergy (with or without CCS) are expected to significantly increase competition for land and water resources, resulting in increased food security risks and land degradation (Hurlbert et al., 2019). For this reason, sustainable forest management is vital to ensure the long-term viability of forest land to help in a wide array of ecosystem services as well as providing feedstock for bioenergy.

6.4 Peatlands/organic soils

It has been reported that approximately 47% of peatlands in Ireland have already been destroyed by human actions (Fernandez Valverde et al., 2006). Despite the considerable loss of peatlands, in a European context, Ireland is still a peat-rich country, and GHG emissions from this sector are much higher than in other European countries. However, a robust system for accounting for emissions is not in place in Ireland as it is in countries such as the UK and Germany (Renou-Wilson et al., 2021). Ireland in this regard should increase the spatial and temporal duration of measurement and should install monitoring systems to capture observational data. The estimated carbon stock held in natural and managed peatlands in Ireland is 2,216MtCO_2, with estimated contributions of 42% from raised bogs, 42% from lowland blanket bogs and 15% from mountain blanket bogs. Traditionally, peatland ecosystems are net sinks for atmospheric CO_2 and sources of CH_4 emissions (Christensen et al., 2012). This interplay in gas exchange has helped in the regulation of the global climate, i.e. giving a cooling effect on the atmosphere (Renou-Wilson et al., 2021).

Extraction of peat for fuel and agricultural applications has caused disruption to peatland ecosystems. This leads to extensive emissions from soil and subsequently lowers the water table significantly (Renou-Wilson et al., 2019). Hence, the protection and restoration of peatlands is vital in the transition towards a climate-resilient and climate-neutral economy.

Among the various types of peatlands found in Ireland, cutover bogs hold the largest stock of organic carbon ($tCha^{-1}$) after natural peatlands. This is despite bogs having shallower peat depths than other peatlands and establishes the importance of peat depth as a key indicator in measuring emissions in this sector (Renou-Wilson et al., 2021).

The prevention of oxidation of peatlands is necessary to prevent peatlands from getting degraded and preserve them. Several projects aimed at the rewetting and management of peatlands to facilitate restoration are in progress in Ireland. The LIFE Multi Peat project is an EU-funded consortium including Ireland whose aims are the large-scale restoration of peatlands, increasing the knowledge base and techniques for halting further emissions from the peatland sector, and the development of effective policy tools pertaining to peatland security and mitigation of GHG emissions. In Ireland, approximately 217ha of peatlands is to be hydrologically restored within this project, equating to 447tCO_2-eq per year of carbon sequestration (European Commission LIFE Public Database, 2021).

Peatlands cover 20% of the Irish landscape and store between 53% and 61% of total soil carbon stocks. In total, 80% of peatlands have been drained for peat cutting, afforestation and conversion to agricultural use. Lowering the water table leads to an increase in peat decomposition and associated soil CO_2 emissions (Minkkinen et al., 2008; Oleszczuk et al., 2008). CH_4 emissions usually cease after drainage (Von Arnold et al., 2005) whereas N_2O emissions may increase, particularly on fertile sites (Martikainen et al., 1993). Furthermore, disturbance is known to increase carbon losses in drainage waters (Yallop and Clutterbuck, 2009). What makes these soils so significant is the potential for GHG emissions and the prospective reduction in emissions through changes in management. Theoretically the rewetting of such sites would be desirable; however, the economic sustainability and impacts at a wider catchment scale must be considered, and the site-specific nature of restoration at multiple scales is emphasised. The Teagasc MACC analysis estimated that the cessation of drainage on 40,000ha would lead to emission avoidance of 0.44MtCO_2-eqyr^{-1} at a cost of €10.9 per tonne of CO_2-eq avoided (Emmet-Booth et al., 2019).

Based on the understanding of detrimental effects associated with drainage-based agriculture in wetlands, the EU Peatlands & CAP Network (2021) proposed ‘paludiculture’ as an agricultural practice making use of wet and rewetted peatlands, and minimising the CO_2 emissions and subsidence. A study by Paul et al. (2018) analysed the total annual emissions from histic and humic soils, using a modified version of the ECOSSE model, as 8.7 and 1.8TgCO_2-eq, and results indicated that,

if half the area of drained histic soils was rewetted, an annual saving of 3.2TgCO_2-eq could be achieved. Likewise, if half of the deep-drained, nutrient-rich grasslands drainage spacing was decreased to control the average water table at −25cm or higher, annual savings would amount to 0.4TgCO_2-eq (Paul et al., 2018).

The EPA-funded Soil Organic Carbon and Land Use Mapping (SOLUM) project is aimed at analysing the impacts of LULUCF on soil organic carbon (SOC) stocks and GHG emissions. The research utilises the available land use data monitoring tools with remote sensing data products to provide a robust land use and soil inventory for Ireland. The key findings from the study were that monitoring of carbon stocks and associated stock changes in SOC were best done by combining ground-based measurements, modelling activities and Earth-based observation techniques for precise estimation. It was also recommended that the tier 2 emission factors used in the study were better suited for reporting SOC stocks due to contrasting trends noted in the current analysis (Saunders et al., 2022).

6.5 Life cycle impact of agri-food products

Fertiliser manufacture no longer takes place in Ireland, and all fertilisers are either imported as a finished product or only undergo further blending in Ireland. Embodied emissions result from hydrogen in the form of ammonia, which is used to make fertilisers; approximately 560,000 tonnes of nitrogen-containing fertilisers were used in 2020. At present, this fertiliser is manufactured across the EU using hydrogen derived from natural gas (Yara International, 2017).

Ireland has a dependence on import markets for procuring protein feeds and dietary supplements for livestock maintenance. In 2021 the total import of such feeds was 4,112,092 tonnes (Department of Agriculture, Food and the Marine, 2022a), which comprised mainly soyabean and maize products imported from Argentina, Brazil and the USA. The approximate emissions of North American and South American maize production are 4.0tCO_2-eqha^{-1} and 27tCO_2-eqha^{-1}, respectively (Teagasc Tillage Crop Stakeholder Consultive Group, 2020). Globally, the need for the accounting of GHG emissions of food consumed away from producer regions has increased. Recommendations are inclined towards the adoption of trade-adjusted emissions of food/feed items at global, regional and national levels (Foong et al., 2022).

7

Pathways to a Climate-neutral Ireland

Climate Neutral Ireland

Policy

We have the political ambition

Evidence

We know there are technical and feasible pathways in energy but evidence in agriculture and land use is limited

Economics

We know there are economic opportunities but also costs and impacts that must be managed

Society

We must bring everyone with us; citizens, communities, businesses, farmers, etc.

Key messages

There is a crucial gap in the literature for studies examining climate neutrality pathways for Ireland. There are only nine existing studies of net zero pathways for Ireland: six focused on the energy system (section 7.1) and three on agriculture, forestry and other land use (AFOLU) (section 7.2). There are currently no complete climate-neutral pathways.

A wide range of mitigation options are required. Renewable energy combined with electrification of heating and transport are a key element but not sufficient. Existing and new energy carriers are needed for heavy transport, industry, planes and ships.

Technological feasibility was not found to be a limiting factor in achieving rapid deep decarbonisation in the energy system studies reviewed. Economic growth can be maintained in Ireland while rapidly decarbonising the energy system. The social cost of carbon needs to be included as standard in the valuation of infrastructure investment planning by government and private investors.

Demand-side reduction in hard-to-decarbonise sectors (agriculture, freight, industry, aviation and shipping) can reduce the burden on supply-side measures and reduce the need for CO_2 removal. Lower energy demand scenarios have been modelled for Ireland; these demonstrate how demand reductions can reduce the mitigation burden while also offering co-benefits for society.

For non-energy emissions, in particular agriculture, a deep decarbonisation strategy is urgently required. There has been limited coverage in the Irish scientific literature to date outside CO_2 emissions in the energy sector.

The journey to a net zero energy system is very hard. There will be difficult choices ahead. Infrastructure such as grid must be built, large investment must be sought, renewable fuels found and homes and businesses transformed. Without these changes and societal and political support, a net zero energy system cannot be achieved.

The pathway to 2030 is clear, but beyond that there are still choices to be made on the role of certain technologies (e.g. areas not suited to electrification, carbon capture and storage, and negative emissions), and strategies needed for significant emission reductions in agriculture and land use.

There is a gap in the literature for studies assessing integrated net zero GHG emission pathways for Ireland. Existing studies have looked at energy (CO_2 emissions) and agriculture and land use (CO_2, CH_4 and N_2O emissions) separately. Within this, there is also limited evidence on society-wide configurations of a net zero energy system or net zero scenarios in agriculture and land use.

To date, there has been only six net zero energy system studies (Yue et al., 2018b; Glynn et al., 2019; Ó Gallachóir et al., 2020; Yue et al., 2020a, 2020b; Gaur et al., 2022a). This is in part reflective of the evolving nature of the problem. Some earlier studies investigated an 80–95% reduction in CO_2 as opposed to net zero (Chiodi et al., 2013). In AFOLU, there are just three such studies (Duffy et al., 2020b, 2022a; Haughey, 2021).

As introduced in section 1.2.1, computer-based models of emissions and the energy system are useful tools to provide scenarios or pathways of different climate mitigation options. For an overview of the existing models and tools available in Ireland, see Annex A.3.

7.1 Current pathways to a net zero energy system

Achieving the ambition of net zero for the energy system will require a significant transformation in the way we produce, use and transport energy. The changes required are not incremental; they are remarkable. Replacing fossil-derived energy vectors with zero carbon energy vectors involves transitioning to alternative means of converting energy from one form to another in each and every aspect of our lives. Evidence shows that the future 2050 energy system must be very different from today's, with electricity as the main energy carrier and with renewables as the main energy source (section 1.2). In hard-to-decarbonise areas, such as some areas of industrial heat and heavy freight, bioenergy plays an important role in the liquid, gas and solid forms. Hydrogen has also been gathering interest as a fuel for applications that are difficult to electrify.

While there are a range of options currently available that can offer substantial emissions reductions, achieving net zero will be challenging. The MACCs (see example in Annex A.3.5) produced by Yue et al. (2020a) highlight that, beyond certain tipping points, the cost of mitigation increases dramatically (Figure 7.1). In another piece of analysis, Yue et al. (2018b) also importantly found that delayed action causes a significant increase in the cost of mitigation and limits the level of feasible decarbonisation ambition Ireland can achieve.

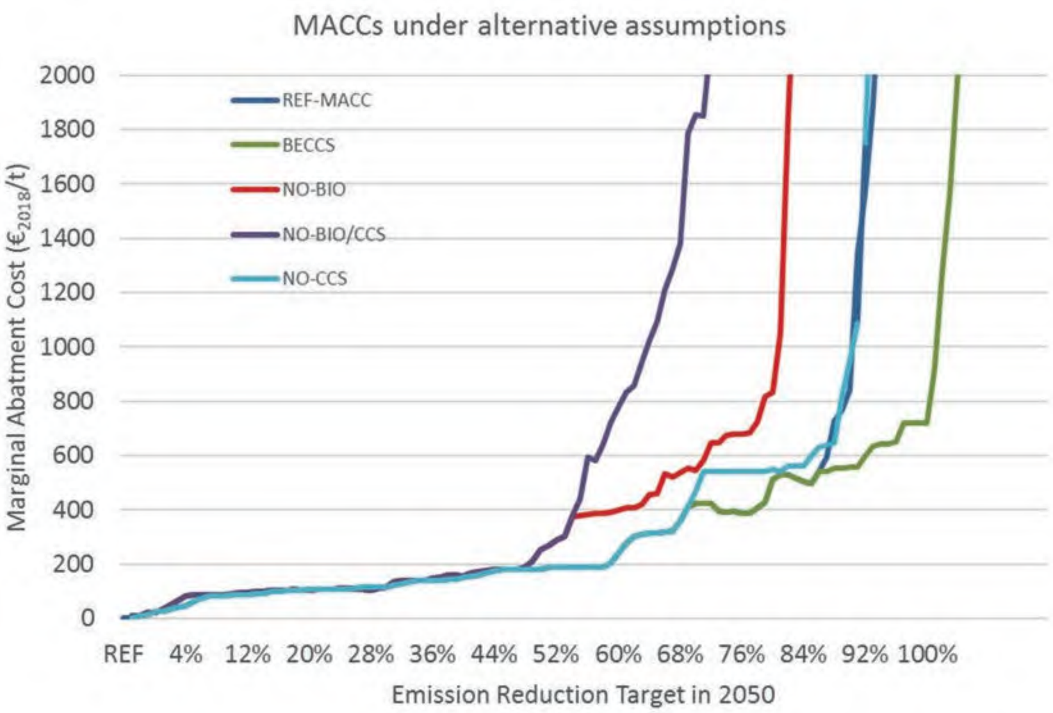
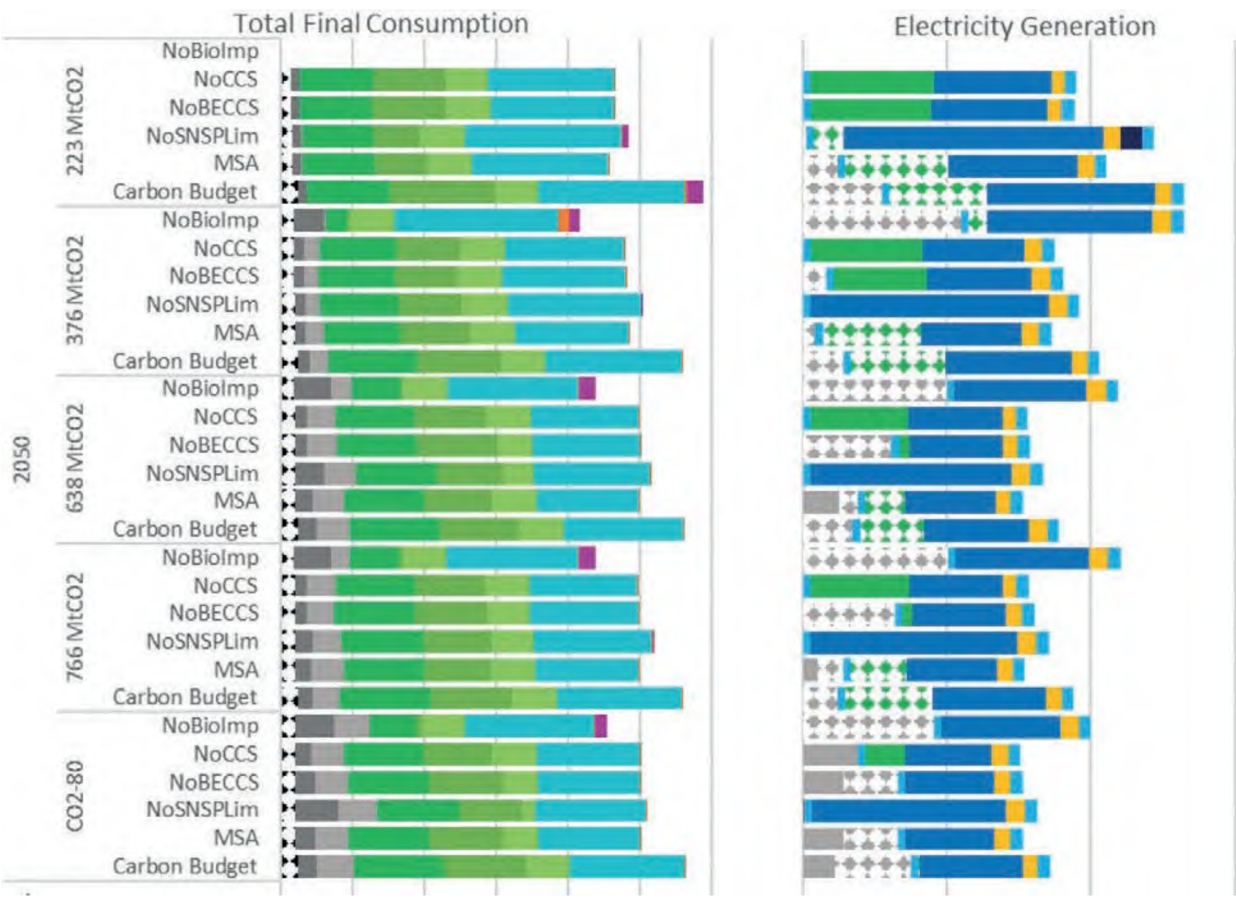


Figure 7.1 Variation in MACCs as a result of different mitigation options in 2050 for scenarios with CO_2 emission reduction targets from 4% to 104% relative to 1990 level. REF-MACC, all mitigation measures are available; NO-BIO-MACC, international bioenergy imports are not available to Ireland and only indigenous resources can be utilised; NO-CCS-MACC, the CCS technologies for power generation are disabled; NO-BIO/CCS-MACC, both bioenergy imports and CCS technologies are disabled; BECCS-MACC, explores the impacts of enabling BECCS. Source: Yue et al. (2020a). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

The cost and level of emission reduction achieved is determined by the technology options made available to the model (Figure 7.1). The scenarios modelled by Yue et al. (2020a) indicate that without bioenergy imports the emission reduction potential is limited to 83%, and without negative emissions from BECCS it is not possible to reach net zero. To achieve a net zero energy system, both Glynn et al. (2019) and Yue et al. (2020a) note the critical role BECCS plays as a source of negative emissions. However, as demonstrated by Czyrnek-Delêtre et al. (2016), including consideration of high land use change impacts will reduce the role of bioenergy. Gaur et al. (2022a) importantly highlight how energy demand reductions can limit the reliance on BECCS.

The size of the mitigation challenge is influenced heavily by demand. A key element of net zero carbon energy systems is thus demand reduction and efficiency improvements (Glynn et al., 2019; DeAngelo et al., 2021; Gaur et al., 2022a). This can be divided into two broad categories: (1) demand reduction that can be achieved by technology switching, including the electrification of heating and transport, or the installation of energy efficiency measures in buildings; and (2) demand reduction that relies on changes in practices, such as choosing active public transport or walking, eating less red meat and flying less. These two categories have different levels of impact on people's everyday lives. Barrett et al. (2021) report that UK energy demand could be reduced by 50% by 2050 relative to 2020 levels without negatively impacting quality of life. Gaur et al. (2022a) conclude from their low energy demand pathway for Ireland that it provides multiple benefits, including faster mitigation action, reduced reliance on negative emissions and improved energy security, while increasing quality of life. It offers benefits for society, including less congestion, more compact and 'liveable' cities and towns, health benefits, and a better standard of living from active travel and more comfortable homes.

Glynn et al. (2019) assessed the energy system and economic impact of a zero carbon energy system for Ireland, consistent with the Paris Agreement. They assessed a range of carbon budgets, from 766 to 128MtCO_2, from 2015 to the end of the time horizon (2070). This provides a range of scenarios looking at different constraints under the set carbon budget (Figure 7.2). They look at the impact of limiting key technologies like bioenergy imports or CCS. All of the decarbonisation scenarios consistent with 1.5°C or 2°C carbon budgets result in a reduction in Ireland's total primary energy relative to the reference scenario of between 18% and 27% by 2030, largely as a result of demand reduction, energy efficiency and fuel switching. In line with global pathways (section 1.2.3.2), electrification plays a central role and subsequently so does renewable electricity. Onshore wind energy and natural gas dominate the generation mix in the short term (to 2030), and in the longer term (beyond 2030) CCS, bioenergy, hydrogen and BECCS become important.



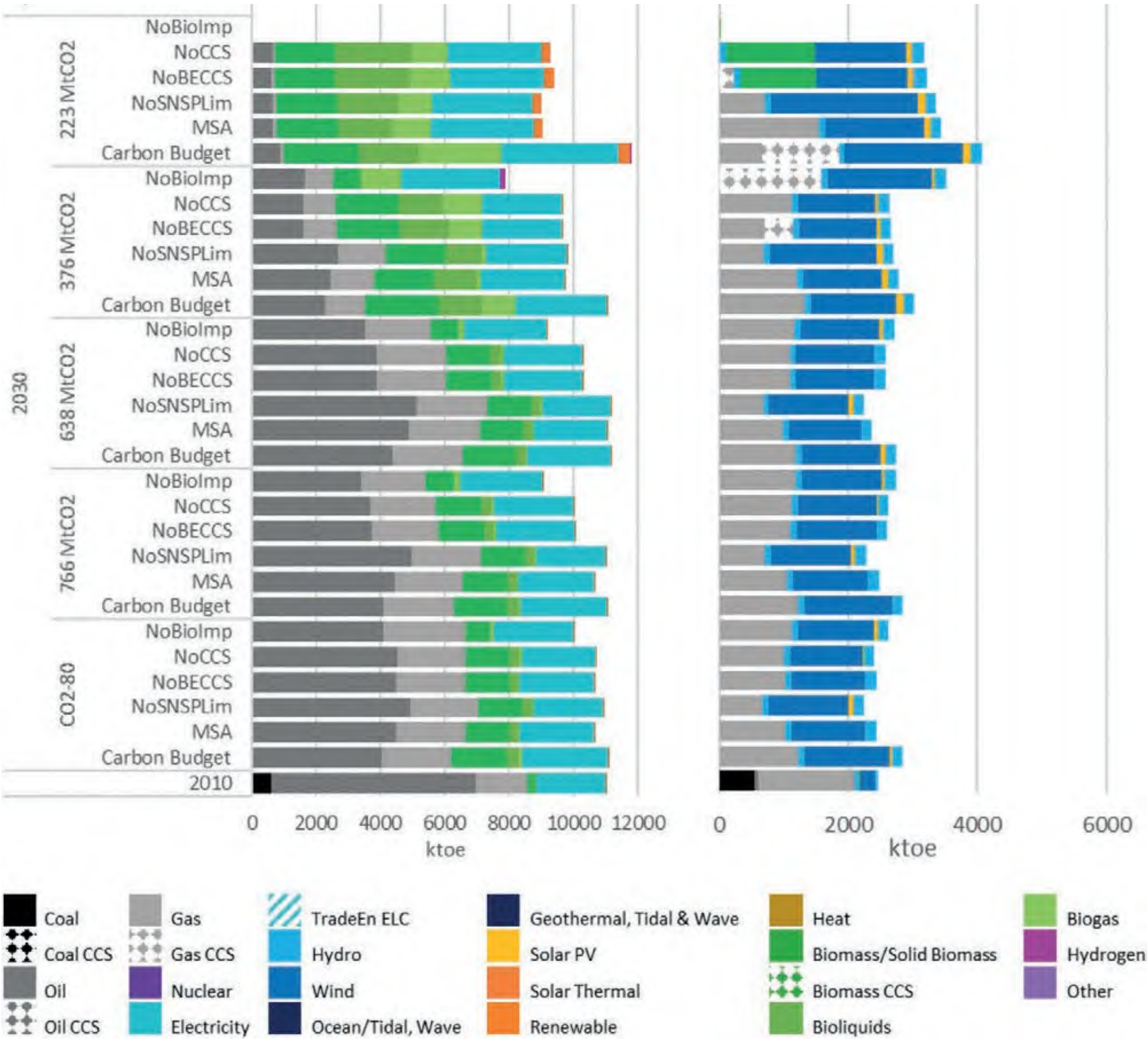


Figure 7.2 Total final energy consumption and electricity generation by fuel per net zero energy system scenario variant. Carbon budget: in this scenario the MACRO-stand-alone algorithm to calculate demand responses and macroeconomic feedback in a general equilibrium is turned off. MACRO-stand-alone: this scenario variant incorporates the MACRO-stand-alone algorithm to calculate demand responses and macroeconomic feedback in a general equilibrium. 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 on 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 allows only domestic bioenergy to be utilised within the energy system and does not allow bioenergy imports. Source: Glynn et al. (2019). Reproduction licensed under the Creative Commons Attribution CC BY-NC-ND 4.0 licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

7.2 Current pathways to a net zero in AFOLU

To achieve net zero emissions in the AFOLU sector by 2050, a number of studies have aimed at developing indicative scenarios (Annex A.3.4). Scenarios were developed using the GOBLIN (General Overview for a Backcasting approach of Livestock Intensification) model approach along with a set of simplified baseline assumptions. These scenarios suggest that achieving net zero GHG emissions in AFOLU by 2050 will be very challenging. Only scenarios that included all (or combinations) of the following measures were able to achieve net zero by 2050: effective abatement of livestock emissions (c.30% emissions decoupling) plus a reduction in ruminant livestock numbers (up to 30%), ambitious organic soil rewetting (up to 90% of drained organic soils) and large areas of afforestation (up to 875,000ha of new forest by 2050). The level of change in the AFOLU system required to meet net zero targets under the indicative scenarios developed here would require major diversification strategies and would benefit water quality, biodiversity and many ecosystem services.

7.3 Key findings

7.3.1 Energy system pathways

While the research literature is limited, there are several common messages that emerge from the available literature in Ireland (section 7.1), the UK (Dixon et al., 2022) and internationally (DeAngelo et al., 2021; Sharmina et al., 2021):

- Technological feasibility is not the limiting factor in achieving rapid deep decarbonisation (Glynn et al., 2019). A net zero energy system is technically possible and economically viable; however, societal blockages (e.g. market barriers, policy/regulatory processes) are slowing the rate of deployment.
- Given the limited supply-side options in difficult-to-decarbonise sectors (agriculture, industry, freight, aviation and shipping), demand reductions are important to stay within carbon budgets (Sharmina et al., 2021).

- While aiming for net zero emissions by 2050, investment decisions in the next 5–10 years are important to prevent carbon lock-in (Glynn et al., 2019).
- The role of electricity greatly expands moving from 20% of end user demand today to up to 65% in some future scenarios (Yue et al., 2020b).
- The electricity system will reach zero emissions first, and after that is likely to need to provide negative emissions (Glynn et al., 2019).
- Some elements of CDR will likely be necessary. The extent of this depends on success elsewhere in agriculture, industry and freight. Low energy demand pathways can also reduce the amount of BECCS needed (Gaur et al., 2022a).
- There are clear options available to us now that need to be rapidly implemented: reduce demand, deploy wind and solar energy, and electrify heating and transport. In the longer term, as we approach net zero, there are still choices to be made around the role of bioenergy, hydrogen, ocean energy, CCS and CDR.

7.3.2 Agriculture, forestry and land use pathways

- Clear policy signals/funding mechanisms are essential in the agricultural sector if farmers are to make investment decisions that facilitate their transition to diversification or low-carbon agriculture.
- Based on the available GOBLIN model scenarios in AFOLU, the current policy targets are not sufficient abatement measures, especially in terms of afforestation.
- When we combine agriculture and LULUCF in Ireland it is particularly challenging, as they are both sources (unlike the average picture in the EU, where LULUCF usually offsets some of the agricultural activity emissions).
- The knowledge gaps in land cover/land use and soil carbon fluxes impede the development of mitigation strategies.

7.3.3 Beyond 2030

In the short term (up to 2030), a focus on electrification and renewable electricity can bring significant emission reductions. However, some areas cannot be electrified and so other options will also be needed as we move towards net zero emissions. Bioenergy in solid, liquid and gas forms can offer useful alternatives across electricity, heating and transport (section 4.5). Hydrogen may also be useful in heavy freight or as a decarbonised gas and storage vector that is generated using renewable electricity, stored and then used in gas-fired generation plants when renewables are not available. The extent these alternatives and CCS and CDR will play in a net zero future warrants further consideration.

There is currently no strategy for deep decarbonisation in agriculture, with the research into mitigation options at very early stages (section 6.1.1.1). As outlined in section 1.2.5, due to the lack of mitigation options available, global mitigation pathways have noted the importance of dietary changes and reducing overall demand. McMullin and Price (2020a) highlight that a significant reduction in CH_4 emissions is now critical to effective climate action, both globally and nationally. The models prescribed for AFOLU sectors, as mentioned in section 7.2, although very comprehensive, do not look into the risks involved with the susceptibility of forestry and the unprecedented burden the farming sector has in the diversification process (e.g. reduction in herd numbers, adoption of agroforestry). This is also aggravated by the lack of data available within the land use sector, especially with regard to peatlands, grasslands and forestry in varying soil types.

A critical gap in current evidence is that there is no climate-neutral pathway for Ireland. The limited studies available have examined agriculture and energy separately. Madden et al. (2021) provide a review of 10 different models that might be used to look at agricultural emissions and conclude that a multi-model approach is needed. McMullin and Price (2020a) reviewed studies on society-wide GHG emission scenarios and developed the GHG-WE tool (outlined in Annex A.3.3) as an open-source model of GHG emissions to provide cumulative CO_2-we under different pathways for key gases (CO_2, CH_4 and N_2O). However, the model lacks the necessary sector details to understand the mitigation pathways.

Global mitigation pathways in IPCC AR6 show CO_2 emissions going to net zero 10–15 years before other GHG emissions (see Box 1.3). Applying that to Ireland, the goal of climate neutrality by 2050 may then imply reaching net zero CO_2 emissions between 2035 and 2040. The energy system would then need to provide negative emissions to balance the residual non-CO_2 emissions (i.e. how much CH_4 and N_2O remains). However, it is not possible for this assessment to provide clear pathways for each GHG emission (in particular CO_2, CH_4 and N_2O) or quantify the extent of negative emissions required, as the evidence is currently lacking in Ireland. An integrated assessment of agriculture, energy and land use is needed (section 9.2.1).

8

The Societal Dimensions of Climate Mitigation

Key messages

This is a societal challenge – not an engineering problem.

Our GHG emissions are driven by our lifestyles: what we eat, where we live, where we work and how we get around.

The responsibility for climate change highlights huge inequality across income groups and countries. Across countries, those least responsible for climate change will be the worst affected by impacts. Within countries, more affluent households are responsible for a significantly larger share of the GHG emissions than the less affluent.

Clear communication of policy objectives is important.

The vast majority of the public are concerned about climate change, but there remains a critical gap between these concerns and investment in mitigation measures.

Climate change is predominantly presented as a political or ideological game within the Irish media, with an emphasis on the personalities (e.g. environmental campaigners) or political parties involved, rather than acknowledging the cross-cutting nature of the challenge.

Relying on individual actions will not be sufficient: radical transformational changes across society are needed.

Open dialogue is needed to unpack areas of tension and ensure that co-benefits are realised.

There have been several important developments to support community energy in Ireland. Although limited, research has shown that people are interested in partnership in decision-making – not simply in being consumers at the end of the line.

8.1 Introduction

We tend not to purchase technologies or support environmental policy based on immediate economic costs only. Other factors will inhibit or enable the implementation of different options. It is therefore important to think beyond cost and technology and to touch on a broader range of issues. Such an assessment reveals which mitigation options can be readily implemented and which face barriers that must be overcome before they can be deployed at scale. In addition, under deep decarbonisation, behavioural changes will play an increasing role, with increased need for flexible demand responses and the level of energy demand determining the extent of our reliance on technologies such as CDR.

The purpose of this chapter is to introduce some of the broader societal implications based on the different pathways outlined in the previous chapters, key policy areas and research gaps identified. This is closely linked to the contents of Volume 4, which offers a more comprehensive synthesis of these critical issues.

8.2 Societal dimensions to our emissions

Our GHG emissions are closely linked to our lives: what we eat, how we keep our homes warm, where we live, where we work and how we get around. Fossil fuels gave us seemingly abundant energy, which has led to often wasteful energy practices. Another key issue is the detachment between our choices or behaviours and the emissions. We take for granted that when we turn on a switch on the socket in our wall it will power devices in our home, without much thought for where that electricity comes from. However, only 100 years ago, Ireland had no electricity.

8.2.1 How our behaviour impacts emissions

"Demand side mitigation is about more than behavioural change. Reconfiguring the way services are provided while simultaneously changing social norms and preferences will help reduce emissions and access. Transformation happens through societal, technological and institutional changes" (IPCC, 2022b, p. 118).

Human behaviour plays a vital role in determining the success of climate mitigation (Bolderdijk and Jans, 2021). Reductions in consumption play a significant role in achieving deeper decarbonisation goals both in the medium term to 2030 and increasingly to 2050 (Glynn et al., 2019). At present, there is no suitable fuel to replace oil in aviation and so the only mitigation option available is a reduction in demand, i.e. making the choice to fly less. Similarly, CH_4 emissions from agricultural livestock currently lack a viable mitigation option, and so a reduction in the consumption of meat and dairy products is the most effective means to reduce emissions. There are other key decisions that contribute to our emissions as well. The size of our housing and density of developments is a key factor behind heat and transport energy demand (Gaur et al., 2022a).

Goggins et al. (2022) challenge these techno-centric approaches to behavioural change, which place too much emphasis on the individual, and highlight the importance of culture in shaping energy practice. Greene and Fahy (2020) highlight that non-energy policies across health, education and work-based institutions have generally resulted in energy-intensive practices, and thus work against energy policies seeking to reduce demand. They conclude that there is a crucial role for (non-)energy policy to support demand reduction by aligning with sustainability goals.

The international literature reflects these points. It has long been established that carbon labelling or improved consumer information is insufficient to encourage actual emission reductions (Upham et al., 2011). People cannot be expected to make the right decisions on products or services when there is so much effort spent manipulating the choices put in front of them, corporate 'greenwashing' (de Freitas Netto et al., 2020) and systems limiting our purchasing power. Relying on individuals will not provide the radical transformation in our consumption patterns needed, and instead policy must make climate-friendly lifestyles the default option. There is a need for policy to regulate advertising, create evidence-based certificates for products and services (Otto et al., 2020), put a price on GHG emissions that reflects their environmental impact, and put protections in place for those without the financial means to benefit from new technologies or products.

8.2.2 COVID-19 and greenhouse gas emissions

8.2.2.1 COVID-19 impact on emissions

While taking a whole systems approach to mitigation, the influence and impact that COVID-19 has had within these different sectors needs to be taken into consideration in current and future research on GHG emissions mitigation. Measures implemented by governments in many jurisdictions to address the COVID-19 pandemic have changed individual habits and activities, and these are reflected in changes in energy consumption (Bahmanyar et al., 2020; Klemeš et al., 2021). For

> *"Demand side mitigation is about more than behavioural change. Reconfiguring the way services are provided while simultaneously changing social norms and preferences will help reduce emissions and access. Transformation happens through societal, technological and institutional changes"*
> *(IPCC, 2022b, p. 118).*

example, across the EU, during the lockdown, there was an increase in domestic electricity demand because of individuals spending more time at home (Bahmanyar et al., 2020). Likewise, pandemic measures led to a reduction in commercial and industrial demands, historically higher than domestic demand. Research is needed to determine the long-term impact of COVID-19 on GHG emissions and whether the reductions achieved can be maintained (Kanda and Kivimaa, 2020).

In Ireland, total energy demand in 2020 fell by 8.7% against a backdrop of a 4.2% contraction of the economy (SEAI, 2021c). This highlights the significant challenges of meeting our carbon budgets, which require an average reduction of 4.8% each year between 2021 and 2025, and then a 8.3% reduction each year from 2026 to 2030 (section 2.4.3).

Another concern is the impact COVID-19 may have on investment in climate mitigation technologies. The development, research and deployment of future technologies, such as carbon capture, utilisation and storage, are necessary, in addition to rapid deployment of currently available renewable energy and efficiency technologies (Mabon and Shackley, 2015; Alcalde et al., 2019). Delaying investment in advanced technologies as a result of COVID-19 could result in years of missed opportunities for a deep cut in emission levels and for jobs in construction and engineering (Bell, 2020).

8.2.2.2 'Build forward better'

As the world emerged from the pandemic, a concept that gathered interest was to 'build forward better' or 'build back better'. This would see large amounts of public investment in energy and climate initiatives to boost economic recovery and ensure that we do not lose sight of the more significant challenge posed by climate change. In the USA, the Biden administration's Build Back Better Plan was a $1.7 trillion package aimed at a variety of social issues, infrastructure improvement and environmental programmes. It sought to make the largest nationwide public investments in social, infrastructural and environmental programmes since the 1930s Great Depression-fighting policies of The New Deal (The White House, 2021). In Europe, the EU's recovery fund, coupled with NextGenerationEU, the temporary instrument designed to boost the recovery, will be the largest stimulus package ever financed in Europe. It will see just over €2 trillion invested to help rebuild a post-COVID-19 Europe that will be a greener, more digital and more resilient.

However, the emissions in 2021 do not reflect a change in direction. Globally, while 2020 saw record-level declines, data for 2021 indicate that global CO_2 emissions rebounded by 4.8% compared with 2020 and reached 34.9GtCO_2, which is just shy of 2019 levels. This is equivalent to 8.7% of the remaining carbon budget for limiting warming to 1.5 °C, which, on current trajectories, may be used up in 9.5 years (Davis et al., 2022; Liu et al., 2022). Similarly, in Ireland, emissions and energy data for 2021 show that we are not headed in the right direction (sections 2.3 and 3.2).

8.2.3 Energy and emissions inequality

The responsibility for and burden of climate change are not evenly shared. Globally, those least responsible for emissions are already experiencing the worst effects of climate impacts. Meanwhile, at a national level, those least able to afford cheaper or cost-saving alternatives (e.g. rooftop solar PV, electric cars) are the most impacted by rising fuel prices. This presents a serious equity challenge.

8.2.3.1 Where do emissions come from?

The responsibility for climate change highlights huge inequality across income groups and countries. The top 1% of income earners (i.e. super rich) by some estimates could have an average carbon footprint 175 times that of an average person in the bottom 10% (IPCC, 2022b). At the household level, those with income in the top 10% are responsible for 36–5% of GHG emissions, while those in the bottom 50% are responsible for only 13–15% of emissions (IPCC, 2022b). There is a critical dual inequality here, as those least responsible (Figure 8.1) are also exposed to the worst impacts of climate change. This highlights a need to align climate and development objectives.

This growing income inequality poses a serious threat and challenge for climate mitigation. Increasing inequality within a country can damage social cohesion and affect the willingness of the rich and poor to accept policies or afford lifestyle changes that benefit climate mitigation (IPCC, 2022b). Moreover, climate mitigation policies must be carefully designed so that they do not deepen existing inequalities.

Lyons et al. (2012) provide an estimate of the distribution of emissions across Irish household incomes, but it is outdated, with 2006 being the year of analysis. Tovar Reaños and Lynch (2019), as part of an investigation into the impact of a carbon tax, used the household budget survey to create four expenditure groups. They estimate that lower-income households' emissions per household would be less than half that of the most affluent group.

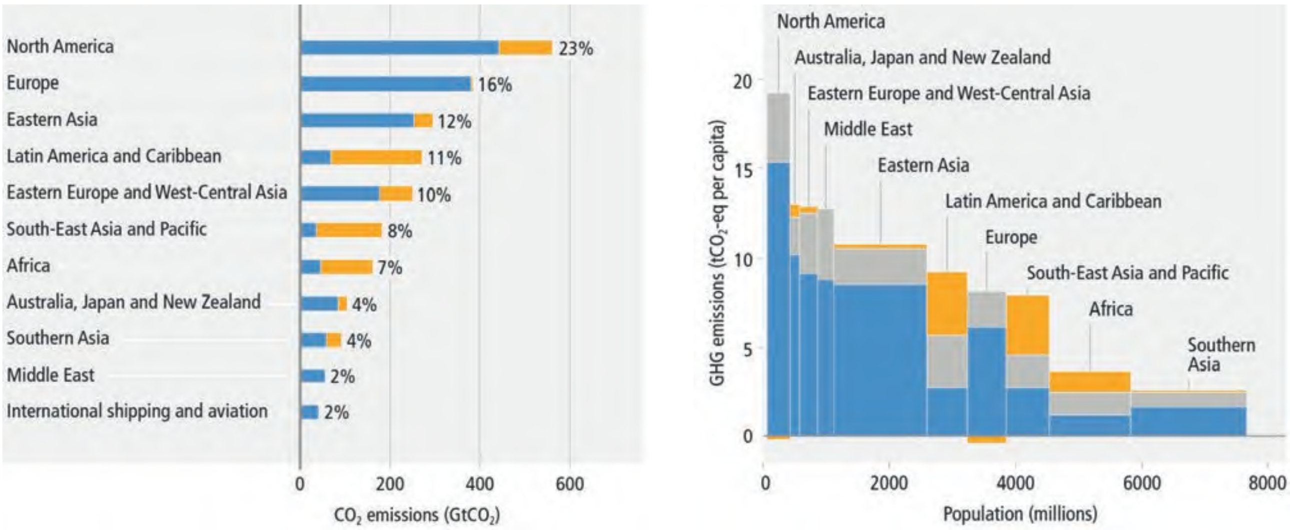


Figure 8.1 Historical cumulative net anthropogenic CO_2 emissions per region 1850–2019 (left) and net anthropogenic GHG emissions per capita per region in 2019 (right). Blue = fossil fuel and industry; yellow = net CO_2 from LULUCF; grey = other GHG emissions. Source: IPCC (2022b; their figure SPM.2, panels b and c).

8.2.3.2 Energy poverty in Ireland

Energy poverty is a serious equity and wellbeing issue. Measuring energy poverty is a difficult task, with no agreed international approach (Tovar Reaños and Lynch, 2022a). Using an expenditure metric, a household is deemed energy-poor if it spends more than 10% of its disposable income on energy (electricity, heating oil, gas or solid fuels) (Barrett et al., 2022). Another indicator would be energy deprivation, which is self-reported instances of a household not being able to adequately heat the home (Barrett et al., 2022).

In 2013, 16% of Irish individuals were recorded as being deprived of heating in the previous year, while 10% were recorded as being unable to keep the home adequately warm (O'Meara, 2016). As fuel bills rise, an increasing number of households are facing the choice between buying essentials like food or school supplies and heating the home. In a recent report from the Economic and Social Research Institute (ESRI), Barrett et al. (2022) outline serious concerns regarding the rising level of energy poverty in Ireland. Their model estimated that 43% of households could be at risk of being 'energy-poor' if prices increased again in the winter. An update to these figures in November 2022 confirmed that 40% of Irish households were experiencing energy poverty (Barrett et al., 2022).

Energy poverty has been shown to be both a consequence and a cause of poor health outcomes. There is evidence of a link between being energy poor and ill health. According to Thomson et al. (2017, p. 14):

> *The energy poor population is statistically more likely to report poor health and emotional well-being than the non-energy poor population, with a higher incidence of bad and very bad SRH [self-reported health], poor emotional well-being, and likely depression.*

A 'fuel allowance' is provided to certain households to lessen the burden of energy costs. These social welfare payments were given over the 2022/23 winter in response to the rising energy costs. However, they do not address the root of the problem. As outlined in the government's energy poverty action plan, which was published in December 2022 (Department of the Environment, Climate and Communications, 2022a), upgrading the energy performance of energy-poor homes is the best way to tackle this problem. 2023 will see a record funding allocation of €148.5 million for the Warmer Homes Scheme (ibid.). The scheme covers 100% of the cost of home energy improvements for eligible households. Since February 2022, the scheme has targeted the worst-performing properties, by prioritising homes that were built and occupied before 1993 and have a pre-works BER of E, F or G (SEAI, 2022b). This is an important way to reduce energy poverty, while improving health and wellbeing outcomes and reducing residential emissions. However, there is a lack of research into experiences of this scheme or its effectiveness (section 9.2.4).

8.3 Societal engagement

"Mitigation policies that integrate and communicate with the values people hold are more successful" (IPCC, 2022b, p. 133).

Renewable energy technologies such as wind energy, bioenergy and solar PV are now mainstream market players, and Ireland as a country is rich in renewable resources. However, the challenges facing Ireland's energy system transformation are more than technical challenges or changes in physical infrastructure and operations. As noted by Schmid and Knopf (2012, p. 671), "the transformation towards a low-carbon energy system constitutes as much a societal effort as an engineer's project." It is often underappreciated how embedded the energy system is in all aspects of our lives. When it is framed as solely a technical issue, a lot of the complexity surrounding the necessary changes to be made is omitted, which has been shown to drive tensions around the placement of specific energy projects (McGookin et al., 2021a). It is important that decisions on the configuration of our future energy system are fair and just, and to outline the co-benefits of the transition in health, wellbeing, improved interconnectivity and economic opportunities (Volume 4 link).

There is a range of understandings of what public engagement means (Calice et al., 2022). It is useful to think of societal engagement in terms of the flow of information or level of control over the process (McGookin et al., 2021b). The following subsections deal with the topic in line with three established frameworks for classifying public participation:

1. communicating/surveying (section 8.3.2) – a one-way flow of information, giving or extracting information, e.g. public awareness campaigns, surveys;
2. consultation (section 8.3.3) – a two-way flow of information, dialogue between different stakeholder groups, e.g. workshops, citizen assemblies;
3. collaboration (section 8.3.4) – ongoing partnership as part of a collaborative process.

Given the complex and far-reaching nature of climate change, proper dialogue is needed for policy decisions to uncover areas of tension and difficulty (McGookin et al., 2022) and a collaborative effort is needed to ensure the smooth delivery of projects (Boyle et al., 2022).

8.3.1 Public reaction to energy infrastructure in Ireland

Ireland's most successful climate policy to date has been the significant growth of onshore wind energy. In the last decade (2010–2020), installed capacity more than trebled, from around 1,300MW to 4,300MW (Sustainable Energy Authority of Ireland, 2020f), which meant that it accounted for roughly 36% of total electricity demand in 2020 (Wind Energy Ireland, 2021). This places Ireland as a world leader for onshore wind energy development and the associated grid integration challenges (Renewable Energy Policy Network for the 21st Century, 2020). However, it has also spawned significant local opposition. The lobby group Wind Aware Ireland, established in 2014 to coordinate local and national protests against wind energy development, represents around 50 opposition groups nationwide (Wind Aware Ireland, 2021a). That same year (2014), the National Economic & Social Council, in its report *Wind Energy in Ireland: Building Community Engagement and Social Support*, called for "A genuine and open participatory process for wind energy" as one of three critical components, along with having a well-informed national energy strategy and intermediary actor support" (National Economic & Social Council, 2014, p.4).

Irish literature on the topic of public opposition to wind energy (Table 8.1) echoes much of the established knowledge in international literature. One of the earliest and most notorious framings of public opposition is 'Not In My Back Yard' syndrome or NIMBYism, which became prominent in international literature and public discourse in nuclear debates during the 1980s (Welsh, 1993; Wexler, 1996). It is often used to describe the phenomenon that, despite public opinion surveys generally showing strong support for new energy infrastructure or climate change mitigation, projects often experience local opposition (Wolsink, 2000). This positions local community opposition as a threat to the greater societal good and something to be overcome. As noted by Lake (1993, p. 91), the 'irrational obstructionism' narrative fails to "recognize it for what it is: an expression of people's needs and fears". It has been extensively criticised in literature over the last two decades as an overly simplistic technocratic approach, highlighted, in particular, by the seminal works of Wolsink (2000), Wolsink (2006, 2007), Devine-Wright (2005, 2009), Burningham (2000), Bell et al. (2005) and Gross (2007).

Table 8.1 *A summary of Irish literature on public opposition to wind energy*

Reference	Issue/theme	Key findings
Brennan and Van Rensburg (2020, p. 13)	Procedural fairness	"respondents want greater levels of participation and engagement in wind farm planning and design than is currently permitted under statutory legislation"
Walsh (2018, p. 242)	Community energy projects	"Emphasis must be placed on both technical and financial support, as well as engaging communities in agenda setting via community development plans that account for local perceptions of what their 'community' means to them"
Brennan et al. (2017, p. 1977)	Lack of trust in actors	"There was a general consensus amongst community participants that wind farm developers were taking advantage of Ireland for their own gain"
Brennan and Van Rensburg (2016, p. 363)	Openness/ transparency	"Respondents exhibit a strong preference for a local community representative that would act on behalf of residents affected by a potential wind farm development and provide information and open dialogue between residents and the developer about the wind farm project"
Van Rensburg et al. (2015, p. 19)	Scale of developments	"the most important project technology variables are project area, rated output capacity, and hub heights"

In line with this growth in onshore wind energy, and in a large part emanating from it, Ireland's transmission system is in need of strengthening. EirGrid, the Irish transmission system operator, originally set out its plan for grid improvements with its *GRIDr25 – A Strategy for the Development of Ireland's Electricity Grid for a Sustainable and Competitive Future* published in 2008 (EirGrid plc, 2008). It had proposed three central 400kV overhead lines and associated pylons to strengthen connections across the country: from south to east ('Grid Link'), west to east ('Grid West') and cross-border between the Republic of Ireland and Northern Ireland ('North–South Interconnector'). It is important to note that one underlying issue driving these proposals is the need to connect the large share of the Irish population/economy living on the east coast and wind energy resources along the west coast. The Greater Dublin Area, which surrounds the capital city, houses around 40% of the Irish population and accounts for over 50% of GDP (Dublin Chamber, 2021).

Important considerations emerged when exploring the broader context and discourse surrounding one particularly controversial proposal to improve the interconnection to the UK and export wind energy generated in the Midlands. As noted by Mullally and Byrne (2015), the proposal fed into a narrative of historical injustice, sparking huge unrest at the notion that Irish communities would bear the cost while the UK would prosper. This was captured in one of the protester's slogans at the time: "Welcome to the midlands, England's offshore wind farm" (ibid., p. 13). Another investigation into the narratives of the supporting and opposing groups highlights how the conflicting conceptualisations of the rural 'resource' and framings (national vs local) means that the two sides "talk 'past' each other rather than 'to' each other" (Lennon and Scott, 2017, p. 104). To the proponents of the development, the value in terms of economic gains is clear; however, to the local opposition, there is no clear benefits that can outweigh the 'industrialisation' of the rural landscape. On from this, questions have been raised about what is conceived to be the 'public interest' and who gets to define it (Lennon and Scott, 2015), which is a particularly challenging issue when projects such as this, which are vital in the national interest, clash with local concerns.

A legacy of this controversy was to conflate, in the public eye, grid developments with wind energy and highlight that the costs and benefits of such energy infrastructure would not be shared equally. The narrative that emerged around external private gains at the expense of the rural communities has been reflected in public opposition campaigns across the country. Increasingly, the national ambition for the reduction of CO_2 emissions is positioned as having little regard for the concerns of rural communities and providing limited local benefits. This highlights the value of paying greater attention to the context and framings surrounding energy infrastructure. As set out by Lennon and Scott (2017, p. 105), there is a need "to work through conflict and preserve difference rather than being paralysed by polarised positions". A more meaningful dialogue and deliberation process may unpack meta-issues, such as the growing inequality between rural and urban areas to develop well-informed climate and energy policy. As Mullally and Byrne (2015, p. 18) conclude, addressing the question of public opposition in Ireland is "not just about the need for better public engagement but also the need to create institutional opportunities to allow for this engagement to take place". Improved communication channels are needed to facilitate a better understanding between top-down and bottom-up stakeholders so that vital national objectives, such as climate policy, are not positioned as coming at the cost of local concerns.

8.3.2 Communicating climate action and public opinion surveys

8.3.2.1 Understanding perceptions of climate change

A number of Irish and European surveys have been conducted in recent years to study public attitudes and perceptions in relation to climate change in Ireland. Nyhan et al. (2022) outline how the Eurobarometer climate change surveys demonstrate a growing concern among the Irish public. In the most recent iteration (2021), nearly one-third (31%) of respondents in Ireland considered climate change to be the single most serious problem facing the world, a much higher proportion than the EU average (18%) (European Commission, 2021a). Climate change ranked first in Ireland, well ahead of any other problem, up from 2019 when it was the second most-mentioned problem behind poverty, hunger and lack of drinking water. Just over 8 in 10 respondents (81% vs the EU average of 78%) believe that climate change is a very serious problem, an increase of 6 percentage points since 2019 and 13 percentage points since 2017.

Science Foundation Ireland commissioned a study to better understand the Irish public's understanding and awareness of climate action. Their research highlighted that 88% of respondents believe that the world is warming up as a result of climate change, with the majority (86%) believing that this temperature increase was due to human activity. However, 49% of those surveyed believe that the information on climate action is confusing and unclear (iReach Insights, 2019). A survey from ESRI found that young people are supportive of more radical emission reduction efforts such as flying less and eating less red meat (Andersson et al., 2022). The EPA also recently commissioned a survey entitled 'Climate Change in the Irish Mind' (Leiserowitz et al., 2021). This included a nationally representative study of the Irish population's attitudes, behaviours, policy preferences and beliefs around climate change. Two key takeaways were:

- A large majority (85%) of people surveyed are worried about climate change, including 37% who describe themselves as 'very worried'. 47% of people surveyed think that people in Ireland are being harmed 'right now' by climate change, and 22% think that it will start to harm people in Ireland in the next 10 years.
- Scientists were the most trusted source of information about climate change among those surveyed. More than 9 in 10 (94%) of the people surveyed said they either 'strongly' (66%) or 'somewhat' (28%) trust scientists as a source of information about climate change. Other highly trusted sources include the EPA (89%), educators (88%), family and friends (85%), television weather reporters (83%) and community leaders (73%). By contrast, the survey found that less than half of respondents trust political leaders (44%), religious leaders (37%), corporations and businesses (32%) and online influencers, celebrities or media personalities (24%) as sources of information about climate change.

As the physical impacts of climate change become more urgent and the subject of wider public concern, a greater understanding of the societal responses will be needed. However, a key remaining gap is the translation of these growing concerns into a willingness to pay for climate mitigation: "There is often mismatch between concerns on climate change and people's willingness to pay for mitigation" (IPCC, 2022b, p. 227). This is best understood through meaningful dialogue and deliberation (section 8.3.3).

8.3.2.2 Communication and the media

"The media shapes the public discourse about climate mitigation. This can usefully build public support to accelerate mitigation action but may also be used to impede decarbonisation" (IPCC, 2022b, p. 127).

Human behaviour plays a vital role in determining the success of climate mitigation (Bolderdijk and Jans, 2021). We need to give people clear messaging on the actions they can take. It is well established that negative messaging on climate change impacts are not the way to go (O'Neill and Nicholson-Cole, 2009). McNally (2020) points to a need for social learning about carbon reduction activities and for communications initiatives promoting collective and community engagement, as well as more discussion of the social, ethical and technological dimensions of climate action in Ireland. They note the importance of "connecting citizens with climate change" (McNally, 2020, p. 2).

Although public perception of climate change has seen growing levels of concern (section 8.3.2.2), our media is yet to reflect this. It is unsurprising that communication on reducing consumption receives very negative kickback when so much of popular culture and media promotes carbon-intensive lifestyles as if they were a basic right. One striking example is the marketing of SUVs through TV and movies, which now sees them representing the majority of car sales. It is very challenging for government messaging to match the power of marketing campaigns that have been using carefully refined techniques over decades.

"The media shapes the public discourse about climate mitigation. This can usefully build public support to accelerate mitigation action but may also be used to impede decarbonisation" (IPCC, 2022b, p. 127).

Another critical issue is the way in which climate mitigation policy is presented in Irish media. Culloty et al. (2019), from their review of Irish newspapers, found that, while climate science is not contested to any great extent, it is often framed as a green or environmental issue. Climate change is predominantly presented as a political or ideological game, with emphasis on the personalities (e.g. environmental campaigners) or political parties involved, rather than acknowledging the cross-cutting nature of the challenge. For example, our dominant car culture means that the pedestrianisation of streets or building of active travel infrastructure is portrayed as a loss, despite scientific consensus on the multiple benefits that modal shifts bring (Mattioli et al., 2020).

8.3.3 Public participation in decision-making

As set out by Watson et al. (2019, p. 20), "Two key principles underpinning climate action in Ireland today are: engaged citizenship and participatory democracy. Two complicating factors are: the need for substantial change and the imperative of acting now."

The growing interest in so-called 'energy citizenship' within national policy, while welcome, has also drawn some criticism. Lennon et al. (2020) note that paradoxically the current national discourse around 'energy citizenship' that seeks to push responsibility into the hands of citizens may in fact be disempowering, as it fails to acknowledge the limited capacity and agency people have for taking part. In an investigation into community perspectives of citizen participation with the energy system, Lennon et al. (2019) found that two key issues were the fact that energy infrastructure is very disconnected from people's day-to-day experience of energy and that opposition may often be motivated by frustration with the decision-making process. The participants in the study expressed concern that "they have very little choice as to how the transition to a low carbon energy system is to be configured", which directly contradicts the notion of 'energy citizenship' (Lennon et al., 2029, p. 24). They thus call for co-production approaches both more broadly in enhanced policymaking processes and locally with community ownership models for energy projects.

A standout example of public participation in the policymaking process is the Irish Citizens' Assembly. Ireland's response to climate change to date has been extremely poor, earning it the title of 'climate laggard', having been consistently one of the EU's worst-performing countries (Torney, 2021). In the light of this, the recent wave of policy and governance innovation is striking (Torney et al., 2020). Most notably, the Citizens' Assembly has received international recognition as an important deliberative forum for examining pressing social, environmental and political issues (Devaney et al., 2020).

Building on the success of previous forums on abortion and marriage equality, the third Citizens' Assembly on climate change was held in late 2017 (Citizens' Assembly, 2018). It brought together a representative sample (across age, gender, social class and regional spread) of 99 citizens to address the issue 'How the State can make Ireland a leader in tackling climate change'. Over two weekends of deliberation, they prepared 13 recommendations, which received overwhelming approval during the closing ballot. Most notably, 89% of the members agreed that there should be a tax on GHG emissions from agriculture, and 80% said that they would be willing to pay higher taxes on carbon-intensive activities if the funds were clearly ringfenced for climate measures and there were protections put in place for those experiencing energy poverty.

While feedback from participants was very positive and complimentary of the 'neutral' space created for deliberation (Farrell et al., 2019), the follow-up on the recommendations has been limited. A Joint Oireachtas Committee on Climate Action was set up in July 2018 to consider the Citizens' Assembly on climate change recommendations, and, significantly, despite some public debate on carbon tax, published 40 recommendations with cross-party support (Torney, 2021). However, there was no clear linkage with those proposed by the Citizens' Assembly. Devaney et al. (2020), in their review of the process, highlight that, while it offers an important step towards more inclusive and collaborative governance, there is a need for a strengthening of communication on how the recommendations are utilised.

The C-CHANGE (Connecting People to Climate Change Action: Informing Participatory Frameworks for the National Dialogue on Climate Action) project provided an international review of best practice in citizen engagement to inform the National Dialogue on Climate Action (Nyhan et al., 2022). It provides guidance on facilitating stakeholders' and citizens' participation in environmental and climate dialogues. The research outputs provide clear and flexible guidelines that can be adapted to different contexts, sectors and audiences by practitioners, researchers and authorities. Boyle et al. (2022) conducted a series of workshops and interviews with community engagement practitioners within national public bodies to understand their experiences and develop guidance. They outline a co-production framework for delivering climate-related infrastructure with citizens, communities and public bodies.

The Climate Act 2021 introduced an expanded role for local authorities in climate action planning. This is an important opportunity for engagement at the county level, which could be better linked to local issues and concerns (Volume 4 link). It is important to note that, at the local level, public participation is also facilitated through the planning system. Any large-scale climate or energy project (wind or solar farm) will be delivered through the spatial planning system and therefore must undergo a planning application and public consultation process.

8.3.4 Community energy

In 2016, SEAI launched the Sustainable Energy Communities (SEC) network, through which mentoring support would be provided to voluntary groups working on energy initiatives (SEAI, 2016). This was an addition to the Better Energy Communities pilot grant scheme that was launched in 2012, encouraging communities to come together to plan improvements to the building stock (SEAI, 2018b). SECs can avail themselves of a grant to cover 100% of the cost of creating an energy master plan for their area, which provides a summary of their baseline emissions and a register of opportunities (SEAI, 2022e). There were over 700 SECs registered with SEAI at the end of 2022 (SEAI, 2020c).

There has been limited research into the experiences of community energy groups in Ireland. Byrne and O'Regan (2020) highlight that the focus on building retrofits in the grant supports available to the groups at the time (Better Energy Communities scheme), meant that only six SECs were taking a holistic approach to sustainability. During their investigation into the motivations behind community-level sustainability projects, they found that the emphasis in national policy on short-term individual financial incentives is misguided. Communities want partnership in decision-making processes that affect their futures and to be regarded as part of the transformation process, not consumers at the end of the line.

Despite the high-level support, community ownership models have struggled to date (Watson, 2020). As with the concerns raised on current concepts of 'energy citizenship', Watson et al. (2019), investigating the barriers to community energy projects in SEAI's SEC network, highlight that the ambition set within the climate action plans to increase the SEC network to 1,500 groups by 2030 is 'out of touch' with the experience of the groups. They highlight the reliance on voluntary contributions and a lack of core funding for coordination and administration as key issues that frustrate these local efforts. Importantly, they conclude that until policy barriers in the form of tariffs, planning, finance, and grid access are addressed, it is unhelpful to continuously talk up community ownership of energy. Given the difficulty in defining the community ownership of energy, Revez et al. (2021) have suggested that better alternatives lie in emphasising meaningful participation and a fair planning process.

The Climate Action Plan 2021 set the target of at least 500MW of renewable electricity to be delivered through local community-based projects. This followed EirGrid's 'Shaping Our Electricity Future Roadmap', which included an expectation for 500MW of microgeneration in Ireland by 2030 (EirGrid Plc and SONI Ltd, 2021), which would represent a significant switch away from what to date has been primarily large-scale developments. Under the new RESS, the 'community benefit fund' contribution of €2MWh–1 offers massive financial support for community projects. In addition, SEAI has introduced significant new supports for groups seeking to develop renewable energy projects through the 'Community Enabling Framework' (SEAI, 2022n), which will address many of the weaknesses outlined here (see further discussion in Volume 4).

9

Moving Climate Mitigation Forward

9.1 Key policy messages

9.1.1 A roadmap for a climate-neutral Ireland

In the most recent assessment report, AR6, IPCC WGIII did not use the term 'climate neutrality' and instead adopted GHG neutrality (Box 1.1 in section 1.1.1). This volume has thus understood climate neutrality to mean GHG neutrality, i.e. annual GHG emissions reduced to net zero by a certain time period. Net zero requires achieving a balance between all sources (energy, agriculture, land use) and sinks of GHG emissions. This assessment found some analysis of how to achieve net zero CO_2 emissions and how to achieve net zero GHG emissions in AFOLU but no roadmap for climate neutrality in Ireland that includes all GHG emissions together. An important consideration within this is the lack of a clear definition for climate neutrality.

9.1.2 We are not on track

Ireland's GHG emissions in 2021 rebounded significantly, not just returning to pre-COVID levels but exceeding 2019 emissions (section 2.3). If this trend continues it will become increasingly difficult to meet the carbon budgets (section 2.4). Initial estimates indicate that 47% of the first budget was spent within 40% of the time frame (Figure 9.1; section 2.4.3).

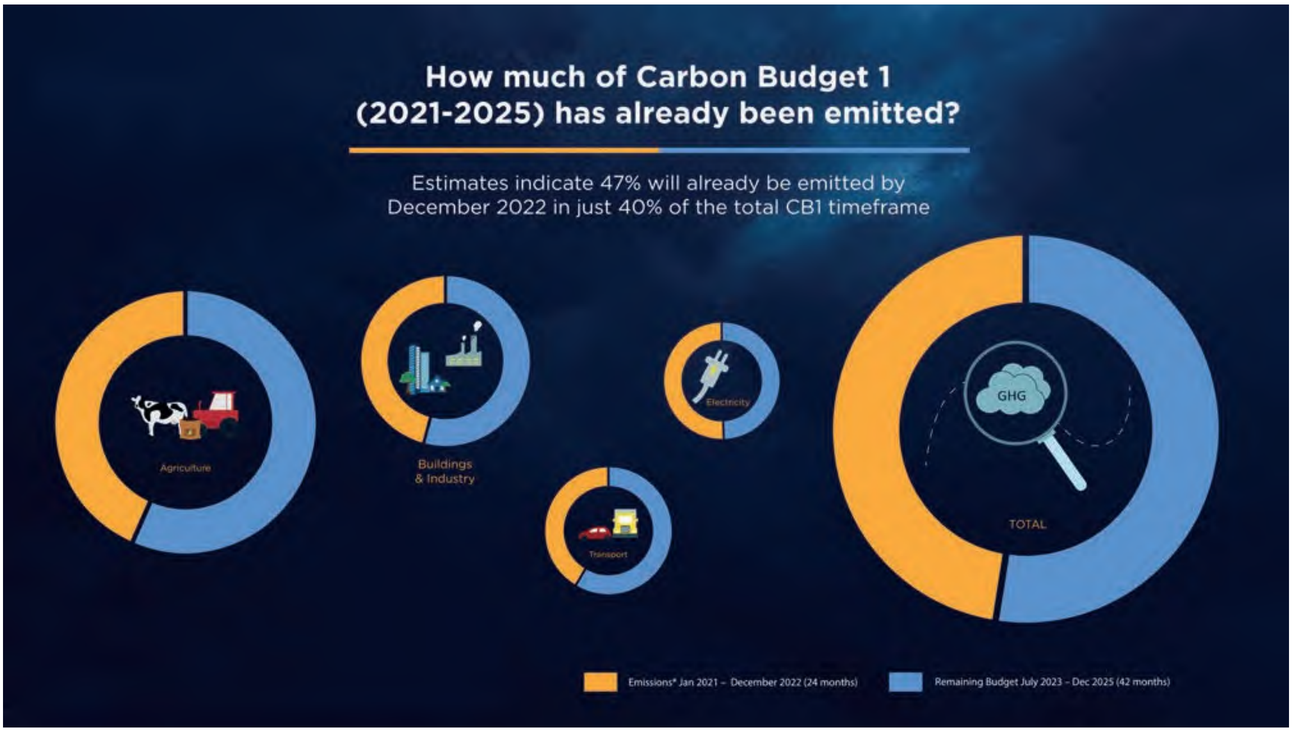


Figure 9.1 Estimation of carbon budgets used by the 2021–2025 time frame. (Source: MaREI Centre)

9.1.3 Gap between climate ambition and climate action

"Climate change mitigation is accelerated when attention is given to integrated policy and economy-wide approaches, and when enabling conditions (governance, institutions, behaviour and lifestyle, innovation, policy, and finance), are present" (IPCC, 2022b, p. 128).

The Climate Act 2021, which put the target of a 51% reduction in GHG emissions by 2030 relative to 2018 and an ultimate goal of climate neutrality by no later than 2050 into law, received widespread political support. On 16 June 2021, the Bill was passed in the Dáil Éireann, with 93% of votes in favour: Tá, 129; Níl, 10; Staon, 0 (House of Oireachtas, 2021). That means that 93% of politicians agreed to the targets set out in the Act; however, what that means in terms of a transformation of Irish society remains poorly understood.

The political consensus on long-term emission goals is not always reflected in individual measures. Party political tensions are evident in discussions around carbon tax, wind farm development guidelines, electricity and gas network development,

bioenergy and energy demand reduction, particularly where demand reduction challenges current models of economic development.

Two examples highlight the tension between economic development and climate mitigation. The forecast growth of data centres represents a challenge to Ireland's emission targets (section 4.3.1). Similarly, the debate over the expansion of a Glanbia Cheese Ltd factory in County Kilkenny demonstrates a mismatch between economic development priorities and emission reduction goals. It is within the planning system where many of these difficult decisions and conflicts will come to the fore (section 9.1.10.2).

These tensions call for new analysis (section 9.2.7) and more joined-up thinking across government policy to ensure that everything is ultimately aligned with the carbon budgets, annual targets and long-term objective of climate neutrality. Policy at all levels, from national down to local authority and spatial planning decisions, needs to align with the long-term climate objectives.

9.1.4 Looking beyond electrification

Ireland has been successful in integrating renewable generation into its electricity mix (section 3.4.1). However, decarbonisation in the areas of heating and transport has proven to be more difficult (section 3.4). Ireland's national policy has placed the electrification of heating and transport at the centre of our future energy mix (section 4.4), and the necessary upgrades to the electricity network to support this while integrating renewables are well established (section 4.3). In contrast, the choice of fuel in hard-to-electrify applications and for back-up is less clear. While there is extensive Irish research on bioenergy (section 4.5), it receives less policy attention. There are other emerging alternatives in district heating (section 4.6) and hydrogen (section 4.8) that will also need to be considered.

9.1.5 Carbon dioxide removal

At a global level, preventing warming above a temperature goal sets a finite limit on total emissions of CO_2 from human activities (section 1.1.1). In the event that some sources of GHG emissions cannot reach zero or this budget is exceeded, then negative emissions will be needed either to achieve a 'net' balance between sinks and sources or to compensate for the overshoot. Similarly, at a national level, negative emissions can either help cover difficult-to-decarbonise sectors or make up for the debt after exceeding the country's share of the global carbon budget.

McMullin et al. (2020a) identify a significant gap between mitigation options that are currently regarded as feasible, and what would be needed for our minimal 'fair share' international contribution in responding to the global climate emergency. They call for greater clarity from policy on the extent to which our net zero pathways will rely on negative emission technologies, which are not yet commercially proven at scale. In the absence of integrated climate-neutral pathways, it is not possible to know what scale of CDR will be required. Further research is needed to examine the amount of negative emissions that can be provided by forestry, land and the energy system (section 9.2.1).

9.1.6 Agriculture and land use

There is currently a key evidence gap in how to achieve climate neutrality in agriculture. Within the EU, Ireland has higher than average emissions of CH_4 and N_2O because of the large livestock sector. Innovations in the development of feed additives to inhibit enteric CH_4 protection are under way and the use of protected urea to reduce N_2O emissions is still in the early stages of implementation. There is currently a key evidence gap in how to achieve climate neutrality in agriculture. Low-emission fertilisers, optimal use of slurry and planting legumes to improve nitrogen use efficiency are recommended. Optimal use of no-regret livestock management measures, such as increasing the dairy EBI, improving herd genetics, improving animal health and promoting efficient feeding strategies, will help in reducing GHG emissions. Diversification within the sector will be necessary to achieve deep emission reductions. It is very important because this can reduce livestock numbers and enable different land use strategies, such as bioenergy and agroforestry.

LULUCF in Ireland is a source of emissions rather than a sink. Different combinations of afforestation, rewetting of organic soils and enhancing carbon sequestration in mineral soils are the primary means to achieve net zero emissions within LULUCF. Additional analysis of drainage and the nutrient status of peat soils would help in understanding the total potential of reduced emissions and increased removals that can be achieved via improved land management.

Transitioning from current intensive agricultural practice to mitigate GHG emissions in Ireland requires protecting farmer incomes and underpinning food production, while delivering on a range of policy objectives. This is in line with the aims of a previous Climate Action Plan (2021) of achieving 51% reductions in overall GHG emissions by 2030 and reaching net zero by 2050, with policies aimed at protecting farm safety and efficiencies at the same time. The EU Common Agricultural Policy (CAP) has been subject to a range of reforms and corrections to reflect other EU countries, and the main policies to be aligned within the agricultural sector are the European Green Deal, the EU Biodiversity Strategy for 2030 and the EU Farm to Fork Strategy.

The government has recently adopted the CAP Strategic Plan 2023–2027 (Department of Agriculture, Food and the Marine, 2022b), which is mainly aimed at ensuring continued viability of Irish agriculture and maximising the environmental/social sustainability of the sector. These actions are also in line with mitigating the recent increases in the costs of feed and energy owing to the war in Ukraine, and funding of €10 billion has been allocated for this.

9.1.7 Putting a price on carbon

"Carbon pricing is effective in promoting implementation of low-cost emissions reductions" (IPCC, 2022b, p. 127).

Transitioning from fossil fuels to renewable energy and energy efficiency improvements are important components of the EU's action plan for reducing carbon emissions. Carbon pricing is an efficient instrument to deal with the externality of GHG emissions. The EU ETS, which caps the overall level of emissions and then permits trade among emitters, provides a mechanism to price CO_2 emissions at a European level (Forbes and Zampelli, 2019). The price of allowances in the EU ETS has been rising recently, and some analysts see EU carbon allowance prices rising to a range of €56–89 per tonne of CO_2 by 2030 (Sheppard, 2021). If that happens, the implications for emissions in the sectors covered could be significant. These sectors account for about 45% of emissions in the EU. They include power and heat generation and industry sectors, including oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals. Certain N_2O emissions and emissions of perfluorocarbons are also covered. In 2018, the top 88 participants in the EU ETS in Ireland accounted for about 28 million tonnes of carbon emissions, representing approximately 46% of total national GHG emissions (EPA, 2021b).

Many countries have introduced carbon taxes to cover carbon emissions not included in the EU ETS, including Ireland. Irish government policy is to introduce continuous increases to the carbon tax to €100 per tonne of CO_2 by 2030. The revenue raised from carbon taxes will grow commensurately and can be put to many uses, including climate justice purposes, protecting vulnerable groups, clean energy innovation, supports for households and business investment in decarbonising technologies (de Bruin, Monaghan and Yakut, 2019; Tovar Reaños and Lynch, 2019). Tovar Reaños and Lynch (2022b) suggest that accounting for the avoided economic damage associated with climate change, which disproportionately impacts low-income households, would mean that the tax is not regressive. Tovar Reaños and Lynch (2019) importantly highlight that a 'carbon cheque' that distributes the revenues equally to every household leads to small changes in income inequality, while a targeted mechanism that directs more of the revenues towards less affluent households would reduce income inequality. This is in line with the key message from IPCC WGIII AR6 that "Carbon pricing is most effective if revenues are redistributed or used impartially" (IPCC, 2022b).

In addition to carbon taxation, some have suggested a need for government rationing of the remaining carbon budgets. McMullin and Price (2020a) note that to drive innovation, overcome carbon lock-in effects and increase social acceptance, existing demand measures (efficiency and carbon pricing) could be complemented by equitable supply-side regulation of imported fossil fuel and reactive nitrogen.

9.1.8 Climate and energy financing

"Finance to reduce net GHG emissions and enhance resilience to climate impacts is a critical enabling factor for the low-carbon transition" (IPCC, 2022b, p. 133).

Low-interest loans will be important to support homeowners investing in home energy improvements or EVs. Careful consideration should also be given to how large-scale infrastructure projects are costed. The carbon impact of developments needs to be more carefully considered in the costing (sections 9.1.10.2 and 9.1.7). The science is clear that the cost of mitigation is significantly less than the costs that climate impacts will bring (Box 1.3 in section 1.2.3.2). However, current financing approaches that discount future costs do not reflect this reality. The sectoral ceilings introduced with the carbon budgets are an important mechanism to ensure that, across government, all spending is ultimately aligned with our long-term climate objective.

9.1.9 A fair and just transition

"Explicit to equity and justice is salient to both social acceptance and fair and effective policymaking for mitigation" (IPCC, 2022b, p. 127).

A key element of public engagement is identification of the potential barriers to and losers in the transition to a carbon-neutral society. When policies are perceived as unfair or having a disproportionate impact on particular communities, then they are unlikely to succeed. A just transition whereby vulnerable groups are protected and encouraged to participate will be vital in climate mitigation policy. This requires new approaches to research to provide ideas grounded in people's experiences (McGookin et al., 2022). With regard to the AFOLU sector, there is an urgent need for a future vision aimed at maximising opportunities towards a just transition for farmers, and trade-offs related to transformational changes in Ireland's path towards climate neutrality should be aptly incentivised and encouraged.

9.1.9.1 Energy poverty

As noted in section 8.2.3.2, the rate of energy poverty is on the rise in Ireland. This poses a serious equity issue. There is a danger that inequality deepens as more affluent households reduce their energy costs by availing themselves of grants for new technologies (e.g. solar PV or EVs) while lower-income households unable to afford the upfront cost experience increasing energy bills. Carefully designed policies are needed to ensure that the benefits of climate mitigation are evenly shared across income groups and that key measures such as the carbon tax (section 9.1.6) do not become divisive.

9.1.9.2 Just transition

A vital part of the end of peat harvesting and power plant operation in the Midlands is a just transition for the workers and communities. When it comes to managing the transition, there is no readily available template, as every town and region has its own context. There is a lack of international consensus on how best to manage these processes, which is a great opportunity for Ireland to show leadership (National Economic & Social Council, 2020c). An inclusive, place-based approach is necessary, with an overall focus on regional development and investment into new sustainable enterprises that will offer high-quality jobs (National Economic & Social Council, 2020a, 2022).

On from minimising the impact of the transition on vulnerable workforces, there is also the balancing of rural and urban concerns. Faulkner et al. (2019), in their review of Ireland's recovery from the financial crisis of 2007/08, highlight a growing divide between rural and urban households. Energy and climate policies risk becoming an increasingly divisive issue when they are perceived as a threat to rural communities (McGookin et al., 2022). This calls for improved dialogue and more carefully designed interventions to manage trade-offs and ensure that the benefits are evenly shared across rural and urban areas (McCabe, 2021).

The likely reduction in livestock numbers necessarily calls for new thinking around agriculture in Ireland. Managing this disruption will require a 'just transition for agriculture' (Mercier et al., 2020). To date, discussions on reducing emissions have commonly been perceived to represent a threat to farmers' livelihoods (McCabe, 2021). Policy over the last decade has driven an intensification in dairy farming that is incompatible with a climate-neutral future.

9.1.9.3 Public participation in decision-making

At present, the approach to public participation that dominates Ireland's policy landscape is that of a simple consultation whereby interested bodies and people can make formal submissions. It is a very exclusionary process that favours the interests of organised groups such as industry lobbies, as opposed to people's genuine concerns. For climate policy to be fair and just it must involve proper dialogue and deliberation (National Economic & Social Council, 2020b). Greater effort is needed to engage hard-to-reach groups to ensure that all voices contribute to a shared vision for the future. The local authority climate action plans offer a means to improve dialogue on climate action at the county level (section 9.1.10.1).

9.1.10 The role of local authorities

"Local governments are well placed to develop policies that generate social and environmental co-benefits but to do so require legal backing and adequate capacity and resources" (IPCC, 2022b, p. 128).

9.1.10.1 Climate mitigation planning

Under Ireland's Climate Act 2021, local authorities have been given an enhanced leadership role. One interesting part of the new legislation is a requirement for each local authority to develop a climate action plan that addresses both mitigation and adaptation measures. Local authorities have made good progress in climate adaptation and improving the energy efficiency of their public buildings (Dekker, 2020), but there are serious gaps in capacity and resources, limiting climate mitigation planning (Revez et al., 2022).

First, this will require a better understanding of our GHG emissions below the national level. A critical first step in the creation of the climate action plans is to undertake a baseline emissions inventory for the city or county. This sets a statutory requirement for local authorities to map out the GHG emissions within their administrative area. To date, local authorities have only dealt with their own direct emissions, such as those from buildings and vehicles, which would represent around just 1–2% of total emissions.

Second, it is an opportunity to explore more meaningful forms of public consultation and stakeholder engagement during the development of the plans. The creation of forums, such as the Belfast Climate Commission (Queen's University Belfast, 2021), using creative techniques, such as those from the Imaging2050 project (Revez et al., 2021), offers exciting prospects (see Volume 4).

9.1.10.2 Spatial planning

Getting serious about our climate obligations means that all aspects of current and future development need to align with long-term emission reduction goals (Revez et al., 2022). Spatial planning plays a critical role in supporting reduced transport and heat demand, as well as improving the feasibility of district heat networks (Gaur et al., 2022a). The long-term climate objective and renewable energy targets (section 3.4) are important in setting the direction, but will do little to advance mitigation if the systems and procedures on the ground, including, in particular, the planning system, are not able to deliver projects.

The potential contribution of the Irish planning system to climate action was highlighted by the Chief Executive of the Office of the Planning Regulator during a recent special sitting of the Joint Oireachtas Committee on Climate Change (Cussen, 2021). At present, the placement of renewable energy projects is primarily developer led, which can spark tensions during the planning application process and incurs a financial cost for the developer. One means to address this weaknesses in the decision-making process would be a move to a plan-led deployment: "A national renewable energy roadmap with county-specific targets could provide the basis for designation of Sustainable Energy Zones by local authorities in their development plans" (Cussen, 2021, p. 3). A key benefit of this national 'spatially coordinated strategy' would be to help build "greater consensus on where and how to electrify our mobility, home heating and wider economic system" (Cussen, 2021, p.3).

Glynn et al. (2019) highlight that the social cost of carbon needs to be included as standard in the valuation of infrastructure investment planning, by both government finance departments and private investors. Previous work from the Royal Town Planning Institute, which was co-funded by the Office of the Planning Regulator and Department of Housing, Local Government and Heritage, provides a toolkit and handbook for 'measuring what matters' (Royal Town Planning Institute, 2020). The QGasSP (Quantitative Greenhouse Gas Impact Assessment for Spatial Planning Policy) project aims to produce a methodology that will allow planning authorities to quantify the influence of spatial planning policies on GHG emissions in a consistent manner (Cachia et al., 2021).

9.2 Key research gaps

Research on net zero pathways must occur in parallel with rapid near-term decarbonisation.

9.2.1 Climate neutral pathways for Ireland

There is a clear gap in the literature for studies of climate-neutral pathways for Ireland. There are only nine existing studies of net zero pathways for Ireland, six covering the energy system and three on AFOLU (section 7.2). There have been efforts to include agriculture within the TIMES (The Integrated MARKAL-EFOM System) model (Chiodi et al., 2016). However, the mitigation options explored resulted in less than a 20% reduction relative to 1990 levels (section 7.2). There have also been efforts to model emissions pathways, but these lack the sector details needed for decision mitigation interventions (section 7.3.3).

The EPA with co-funding from the DAFM recently awarded funding to the SELFS project: Sustainable integrated pathways for carbon-negative energy, land and food systems (EPA, 2022c). The 4-year project (running from 2023 to 2027) aims to address this vital gap in evidence.

9.2.2 Deep decarbonisation in agriculture and land use

One of the major concerns in mitigating the emissions generated from the agricultural sector is the high costs associated with adoption of technology relevant to low-emission strategies. The majority of the research, development and innovation projects in this regard are at the prototype demonstration level (technology readiness level 7 and below), and this invariably leads to requiring more funding and resources for launching an operation. The adoption of such innovative technological practices in farming are inclined towards farmers who are losing profit margins (e.g. reducing herd numbers in dairy) and investing a lot of their own resources and time in converting farmlands to a technology-ready level. The available technologies discussed in Chapter 6 are still in an early implementation or development stage. A reduction in CH_4 and N_2O would be a major driver for deep mitigation in Ireland. A significant reduction in herd numbers and diversification of farming methods would be the key enablers for achieving this.

9.2.3 The energy system post 2030

Established technologies such as wind energy, solar PV, bioenergy, EVs and heat pumps will be key in the short term (i.e. 2030 emission reduction targets); beyond that, there is more uncertainty over the pace and scale at which other options will develop. Offshore wind energy is expected to be the backbone of the future energy system (section 4.1.2). The pace at which offshore wind energy is delivered will thus be an important determinant of how quickly we decarbonise. The contribution of other technologies that are not yet proven at scale (hydrogen, ocean renewables, CCS and CDR) is less certain. Both CCS and BECCS feature in existing energy system pathways to net zero (section 7.1), but research on these technologies has been very limited in Ireland (section 4.11).

Looking at the impacts of innovation on renewable energy technology cost reduction, Elia et al. (2021) highlighted the importance of policies tailored to the different stages of a technology's development. Using the example of onshore wind energy, which entered a mature phase in the period covered, it was shown that policy support for the needs of a growing

industry, such as stable support schemes, together with appropriate regulatory and investment environments were more important than direct policy support for research and development (R&D), which played a more important role in earlier periods. A later review found that learning drivers, such as market dynamics and learning by interacting across different stakeholders and geographical areas, were poorly quantified, despite their impact on cost reduction being recognised in the innovation literature (Elia et al., 2021).

9.2.4 Evaluating policy and models

Unpacking why the 2020 targets were not met can provide lessons to guide future mitigation strategies. In addition, looking back over projections or plans that were made for 2020 will provide insights into the limitations of the computer tools that inform policy decisions. There are some international examples of studies retrospectively reviewing UK energy scenarios to show the gap between cost-optimal solutions from a techno-economic model and what actually happened (Trutnevyte, 2016; Trutnevyte et al., 2016).

Ex post analysis, such as that by Dennehy and Ó Gallachóir (2018) or O'Riordan et al. (2021b), could investigate reasons for climate mitigation policy failure. Similarly, agricultural emissions have been going in the wrong direction as a result of policy changes from 2010. Again, more research, such as that by Kenny et al. (2018), could establish the drivers for such mitigation failure. Conversely, Ireland also has examples of successful policies worth further investigation. Although wind energy has repeatedly fallen short of its targets, policy has led to substantial development (Ó Gallachóir et al., 2009).

Another important area is government support schemes, such as the solar PV grant or building energy improvement grants delivered by SEAI. These schemes should be carefully evaluated to ensure that the significant public funding being provided is being fairly distributed and resulting in the intended emission reductions. There are three strands to this: (1) the types of works being carried out to monitor progress towards national targets such as those in the climate action plans, (2) the experience of individuals, groups, households or businesses availing themselves of the grants, and (3) who is benefiting from the schemes or unable to access them. Engagement with projects post/during works can provide lessons that may improve the process, while working with those who may have started an application but not completed it might help improve the accessibility. In the case of EVs, Caulfield et al. (2022) found a concentration of EV charger grants in more affluent urban areas. This means that the supports are not going to the households that need them and raises serious concerns over the fairness of these schemes.

9.2.5 Model development priorities

9.2.5.1 Understandings subnational energy and emissions

There is a lack of good-quality data and analysis available on energy and emissions below the national level in Ireland (McGookin et al., 2021a). Bar the exception of Dublin, which has benefited from Codema's work on a regional energy masterplan and spatial analysis of heat demand, this is a critical gap in both the current scientific evidence and local authority capacity (Revez et al., 2022).

An important area of work would be to investigate ways of improving subnational estimates of energy and emissions, and developing a central dashboard or repository for sharing this information. To support the new local authority climate action plans, SEAI have released the LA-CAP dashboard (SEAI, 2022i), which provides some energy statistics per county (e.g. wind and solar installs), but not the baseline energy and emissions data that are needed. Research is needed into the variety of ways that subnational estimates of energy and emissions can be determined. The linkage or calibration of such a model against national scenarios could help to improve the delivery of vital infrastructure. In addition, it could also be used to improve the delivery of energy master plans within the SEAI's SEC network by providing a means to coordinate energy planning across levels: from the national level down to county level, and then from county to community networks.

Building on this, another interesting area of investigation is the mapping of energy and emissions data through the use of a geographical information system. This would be important for looking at the interaction between climate mitigation and local authority planning, as well as better-informed energy system planning, by identifying clusters of energy demand and areas for renewable energy development. In addition, it offers an opportunity to look at critical issues of equity and distributional justice, such as the overlap between statistical indicators of energy poverty and areas with high shares of low energy-rated homes, the distribution of public investment such as grant supports (section 9.2.4), and areas most at risk of poor air quality.

9.2.5.2 Improving national energy system models

Gaps have been identified in the current suite of energy and climate policy analytical tools available to policymakers in Ireland. Mac Uidhir et al. (2020a) point to the need for accessible and robust tools that can bridge the gap between analysts and decision makers. There is also a need for the industry and services sectors to receive more detailed analysis and for the transport and residential sectors to receive a broader policy analysis, i.e. beyond private car transport and residential retrofitting. The report also identified a need to address the challenges presented by climate change using a systemic approach that incorporates all sectors of the Irish economy, their interactions and their interdependence.

Within the field of energy and climate modelling there has been much debate in the literature on areas for improvement (Annex A.3.6). Within an Irish context, the various tools outlined in Annex A.3 also provides a summary of the key areas for future development identified.

9.2.6 Meaningful public participation

Ireland's citizen assemblies are a standout example of deliberative processes. However, how the recommendations of these are subsequently translated into policy remains a key gap. The process by which policies are formulated and implemented would therefore seem to be an important area of research. Building on research into creative ways of discussing climate futures with citizens (Mullally et al., 2022), further research is needed into ways of improving the two-way flow of information from this process into policy.

Furthermore, much more examples of local deliberative processes are needed to unpack areas of tension and build a shared understanding of what a climate-neutral Ireland should look like. Another element of public engagement is identification of the potential casualties in the transition to a carbon-neutral society. A just transition, in which vulnerable groups are protected and encouraged to participate in the new paradigm, is vital in climate mitigation policy and will require significant research to provide inventive ideas grounded in experience.

9.2.7 Climate and energy financing

Further analysis on the impact of carbon pricing on behaviour and investment patterns in low-carbon technologies and on the use of revenue to drive an efficient, just transition will be necessary. The financing and governance of climate mitigation is also a critical area that warrants more attention. Research is needed to evaluate policy (section 9.2.4) and also to assess what institutions can do to support effective action across all levels of government (section 9.1.10). Most importantly, how the cost of climate mitigation is financed remains an open question. The reliance on individual household investments in home energy improvements and EVs highlights a need for carefully designed financing options so everyone can avail themselves of new technologies, and not just more affluent households.

9.2.8 Alternative economic paradigms

A notable inclusion in the most recent IPCC report was reference to literature on degrowth (IPCC, 2022b). The concept of a post-growth economic system has received a lot of attention in the international literature (Hickel et al., 2021; Lenzen et al., 2022). Studies have highlighted the benefits of demand reduction in meeting emission targets and reducing reliance on CDR (section 1.2.5). A critical gap in analysis to date has been the fact that modelling tools that inform mitigation pathways assume continued growth in GDP/demand (Pye et al., 2021), which poses a significant challenge for renewables. Many have called for an overhaul of our measurement of a country's wealth from GDP metric to one that can reflect planetary boundaries (e.g. GHG levels) and quality of life (Raworth, 2017). There is very limited research on the implications of these alternative economic models in Ireland (Volume 4 link).

Car travel is but one good example of the avoid–shift–improve framework. It can apply across all energy use and to agriculture and land use. It is quite simple: the less the demand, the less effort needed to decarbonise it. However, prioritising 'avoid' challenges traditional economic paradigms. A renewed policy focus on wellbeing and emissions stability, as opposed to the pursuit of GDP growth, would constitute a dramatic upheaval. The impact and resulting restructuring of a post-growth Ireland are gaps in the research to date.

9.2.9 Deep institutional innovation

A narrow focus on effectiveness and efficiency has come at a cost to society and the broader environment, especially as effectiveness has primarily been measured with respect to CO_2 abatement. Societal and broader environmental impacts are not captured in this indicator, which focuses narrowly on GHG mitigation. For example, agricultural management practices need to consider water quality, air quality and biodiversity gains, as well as adaptation, particularly to flood risk and changes in precipitation frequency and intensity. It will be essential to broaden the scope of quantitative indicators and to include qualitative indicators to assess policies, in particular their distributional impact. Research is needed to determine what sort of metrics are appropriate for the assessment and monitoring of policy or planning decisions. Moving away from a focus on cost would represent a transformational shift (Volume 4). Hughes et al. (2021) set out a research agenda for how the main foundational institutions in society might be re-imagined in the face of the climate crisis, to ensure that they fulfil their basic ethical and effectiveness functions. There has also been some research in Ireland into how the institutions of religion (Hughes et al., 2022) and democracy (Harris and Hughes, 2020) may evolve in response to the climate crisis.

9.2.10 Climate action: bringing mitigation and adaptation together

Evaluation of Ireland's policy responses to climate change across relevant sectors since 1996 highlights that a systems approach is needed to address both mitigation of and adaptation to climate change (Dekker and Torney, 2021). The use of 'climate action' (bringing both mitigation and adaptation together) within recent Irish policy stands in contrast to research in this space. These two separate fields of investigation rarely interact. Research is needed on the co-benefits and trade-offs of different mitigation and adaptation measures, and on the ways in which the planning of both can be aligned to support a more rapid implementation of climate action projects or measures.

Annex

A.1 Glossary of Terms

Fossil fuel	**Coal**	Solid black fuel, high CO_2 emissions, used primarily for home heating and electricity generation
	Natural gas	Gaseous fuel, CO_2 emissions are lowest of the fossil fuels but still substantial, widespread gas grid, used for heating, cooking and extensively for electricity generation
	Crude oil	Petrol, diesel and other liquid fossil fuels are derived from crude oil, CO_2 emissions are dependent on end use but high, transport is almost exclusively fuelled by oil
	Peat	Brown/black earthy fuel, very high CO_2 emissions and habitat destruction, harvested for residential heating, and commercially harvested until recently for electricity generation, briquette and horticultural peat production
	Fossil hydrogen	Hydrogen made from fossil fuels, the CO_2 produced can be either released (grey hydrogen) or captured and stored (blue hydrogen), which dictates the climate impact
Renewables	**Biomass**	Refers to biological (e.g. wood, grass, food waste) material that can be used for energy production, considered carbon neutral, although careful life cycle assessments are required
	Biogas/ biomethane	Gaseous fuel made from biomass, chemically very similar to natural gas, careful life cycle assessments are required
	Wind	Large turbines are used to convert the energy of moving air into electricity, mature technology, CO_2 emissions are limited to construction
	Solar	Solar PV arrays convert falling sunlight into electricity, increasingly mature, CO_2 emissions are limited to construction. Another technology, solar collectors, can be used to heat water for homes/industry
Indirect renewables	**Green hydrogen**	Water is split into hydrogen and oxygen using renewable electricity, therefore there are no direct CO_2 emissions
	District heating	Hot water is produced centrally and pumped to users, this can be based on waste heat from an industrial process or by using a renewable energy source. Benefits are economies of scale and utilising otherwise lost energy
	Synthetic fuels	Green hydrogen or another clean energy source is used to create a fuel that acts like a fossil fuel but contains only carbon from the biomass or the atmosphere, thus not contributing to climate change

Bioenergy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.

Carbon budgets are a way of measuring the total remaining additional emissions that can enter the atmosphere if the world wishes to limit global warming to a specific level. They are based on the fact that the amount of warming that will occur can be approximated by total cumulative CO_2 emissions in the atmosphere.

Carbon capture and storage (CCS) is a climate mitigation technology that can prevent CO_2 from being released into the atmosphere from the use of fossil fuels or biomass combustion by capturing it and placing it in geological storage.

Fuel cells are electrochemical cells that can combine hydrogen and oxygen to produce electricity, with the only emission being water. Fuel cells can be used in vehicle propulsion or stationary applications.

Gross domestic product (GDP) is a measure of income generated in a country.

Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change.

Levelised cost of electricity or energy (LCOE) quantifies how much each unit of electricity/energy from a generator must be sold for over a particular time frame, for the investment to be fully recovered, including upfront capital costs, fuel costs and operation and maintenance costs over the lifetime of the development.

Net zero refers to achieving the balance between the amount of greenhouse gases produced and the amount removed from the atmosphere.

Primary energy is the total amount of energy used. It includes the final energy used directly by the end-user, and also the energy 'lost' in transformation processes, such as electricity generation and oil refining, and other losses such as electricity transmission and distribution.

United Nations Framework Convention on Climate Change (UNFCCC) established an international environmental treaty to combat 'dangerous human interference with the climate system' by stabilising GHG concentrations in the atmosphere.

A.2 Key Concepts

A.2.1 What drives energy demand?

As introduced in section 3.1, people do not want energy itself, but rather the services, like mobility, heating and cooking, that energy provides. These are often referred to as energy service demands. Factors that can influence the level of demand include the weather, costs, efficiency, technology/fuel choice and the state of the economy (SEAI, 2021c). Energy supply responds to the level of demand for energy services (heating, transportation and electricity) and how end-users want that energy demand satisfied. Energy service demand is driven primarily by economic activity and by the energy end-use technologies employed in undertaking such activity.

For example, population growth impacts the number of homes we need, which has a rolling impact on the amount of heating, cooking and lighting demand. The amount of energy used in the home will then largely be depend on energy performance of the building/technologies in it, followed by the cost of fuel and household income. In addition, where these homes are located will also influence the number of kilometres people move and travel each year, which feeds into transport energy demand. Heating and transport demand is thus also linked to the density of our settlement patterns in terms of access to services (i.e. how far we travel to work, school or shops) and size of homes.

A.2.1.1 Economic activity

Generally, the larger an economy, the greater the level of energy demand. GDP is the most widely accepted measure of economic activity internationally. Historically, there has been a very close relationship between a country's GDP and its energy demand as a country develops. Industrialisation driven by fossil fuels meant there was a close link between the profits of companies and energy demand. However, more recently, there has been a significant move to less energy-intense forms of economic activity, which means that the relationship is no longer as clear.

The relationship between economic activity and energy demand in Ireland is particularly complex. A large share of our GDP comes from the activity of large multinationals that demand little energy relative to the very large amount of value added in sectors such as pharmaceuticals, technology and, in particular, services[28]. In contrast, an industrialised nation, like Germany, that produces energy-intensive heavy goods and machinery for export (cars, computers, chemicals) currently requires large amounts of fossil fuels in production and transportation.

The mismatch in Ireland between the economic activity of these companies that results in large amounts of value added (i.e. profits) and the very little energy demand was clearly illustrated in 2015, when GDP increased suddenly by 25% from 2014, due to the transfer of intellectual property from multinational companies (SEAI, 2022c). This demonstrates that care must be taken when comparing macro-economic indicators, such as energy demand per unit GDP. To address this issue, the CSO have developed alternative indicators to GDP.

Modified gross national income is an adjustment to gross national income designed specifically to measure the size of the Irish economy (Central Statistics Office, 2022a). It subtracts depreciation on two kinds of assets to exclude globalisation effects: intellectual property and leased aircraft. In addition, it excludes the income of redomiciled public limited companies. These are companies with a permanent office here, meeting the criteria for being an Irish resident. However, their board members do not usually work in Ireland and the companies conduct little or no real activity in Ireland.

Another alternative indicator is modified domestic demand. While modified gross national income approaches GDP from income perspective, modified domestic demand approaches it from an expenditure perspective (Central Statistics Office, 2022b). It is a measure of expenditure in the country less some large transactions from foreign companies that have little impact on the domestic economy, such as trade by aircraft-leasing companies, exports and imports of research and development services, and exports and imports of R&D-related intellectual property rights (Central Statistics Office, 2022b). Modified domestic demand therefore results in a smaller number than GDP, and more truly reflects what Irish homes, business and government are doing. For example, Ireland's modified domestic demand grew by 5.3% from 2014 to 2015, compared with 25% for GDP (SEAI, 2020a).

Figure A.1 shows the historical trends for modified domestic demand, energy prices and final energy demand, each expressed as an index relative to 2005. The figure illustrates changes in economic growth between 2005 and 2020 and shows the effect of the economic downturn between 2008 and 2012.

[28] Services refers to a business activity in which a physical product is not made, rather a service was provided at a cost, such as consultancy, accounting, data analysis and others.

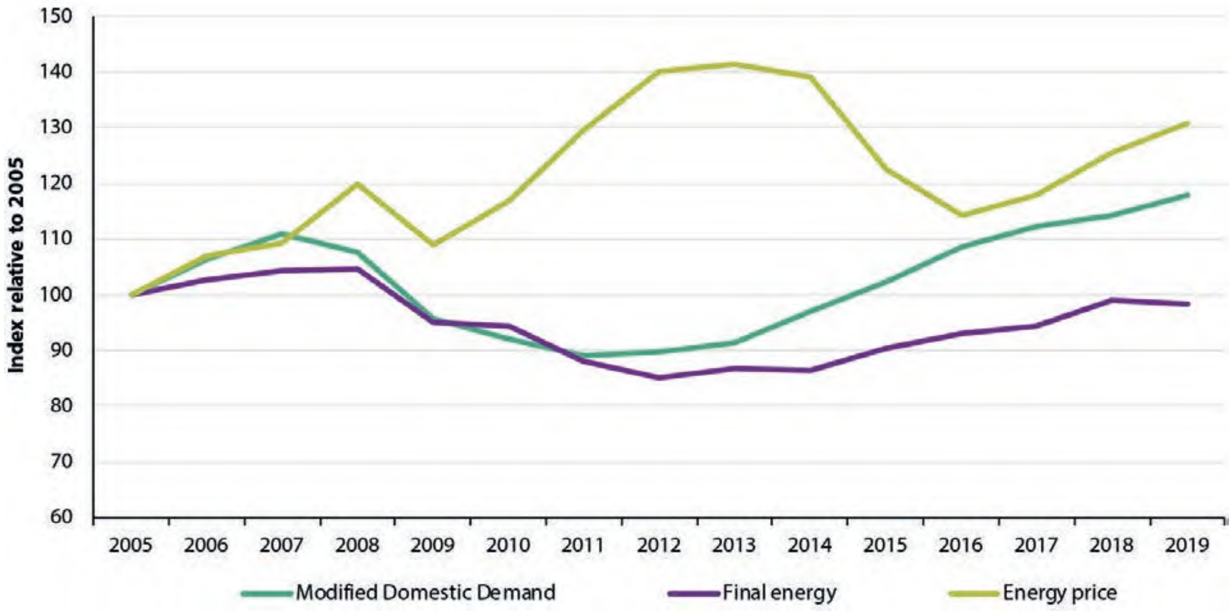


Figure A.1 Index of modified domestic demand, final energy demand and energy price, 2005–2020. Source: SEAI (2021c).

Improvements in the standard of living have also been a factor influencing energy consumption increase since 1998 (Andreoni, 2020). During the Celtic Tiger (1998–2007), GDP grew much faster than energy demand, and the effect was even more pronounced from 2008 onwards, demonstrating a relative decoupling of economic growth and energy demand. This was due to the implementation of energy efficiency measures, and switching from energy-intensive industry, such as construction, steel and fertiliser production, to higher value products, such as pharmaceuticals (Andreoni, 2020).

Between 2014 and 2019, the transport sector was the largest energy demand in Ireland (section 3.2), but in 2020 it fell below the heat sector (SEAI, 2021c). This was a result of the disruption caused by COVID-19, which shows how sensitive the transport sector is to changes in the economy. Economic growth is a strong driver of road freight activity, although it is also influenced by fuel price, commodity type and road infrastructure. Increasing taxes on petroleum-based fuels can act as an incentive for freight operators to focus on improving logistics and operational efficiency, although rising prices for freight operators might also be passed on in the form of a higher prices for the consumer (Mulholland et al., 2018b).

A.2.1.2 Energy intensity

Energy intensity is a measure of an economy's efficiency and shows how much energy is needed to produce a unit of GDP. For instance, if an economy becomes more efficient in its use of energy and its GDP remains constant, then the ratio for this indicator would fall. It is often expressed in kilograms of oil equivalent per €1,000 of GDP. Structural changes to the economy, as has been the case in Ireland, can also impact energy intensity and so it has been highlighted to be a poor proxy for energy efficiency (Filippini and Hunt, 2015).

The least-intensive economies in the EU in 2019, i.e. those using the least amount of energy relative to their overall economic size (based on GDP in purchasing power standards), were Ireland, Denmark and Romania (Eurostat, 2022b). The most energy-intensive EU Member States were Malta and Finland (Figure A.2).

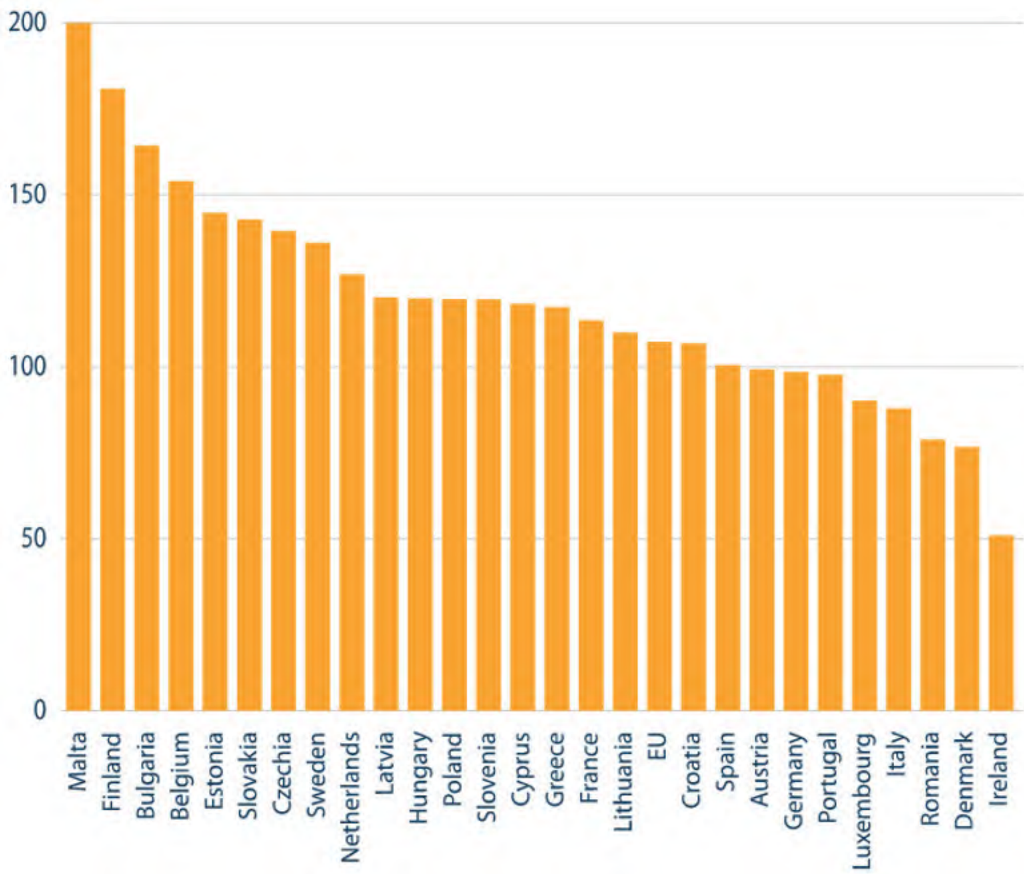


Figure A.2 Energy intensity of EU Member States in 2019 in kilograms of oil equivalent per €1,000 in purchasing power standards. Source: Eurostat (2022b).

There are many factors that influence how trends in energy intensity of the economy evolve, including technological efficiency and the fuel mix, economies of scale in manufacturing and the structure of the economy. Ireland's low energy intensity is a result of the very limited amount of heavy industry (section 5.2.2.1) and large services sector. However, with the large growth in data centres, the demand in the service sector (within the information, computer and technology) is rising significantly (section 5.2.2.2).

In Ireland, the structure of the economy has changed considerably over the past 20–30 years. It has a large amount of high value added sectors, such as pharmaceuticals, electronics and services, and a limited amount of 'heavy industries', such as car manufacturing and steel production (SEAI, 2021c). This results in a more productive economy from an energy perspective, but, critically, does not necessarily mean that less energy is being used overall in the economy or energy-related CO_2 emissions are reduced.

As illustrated in Figure A.3, non-OECD energy consumption has skyrocketed since 1970, while OECD energy demand has stayed nearly flat. This is in a large part driven by the movement of heavy industry from OECD to non-OECD countries.

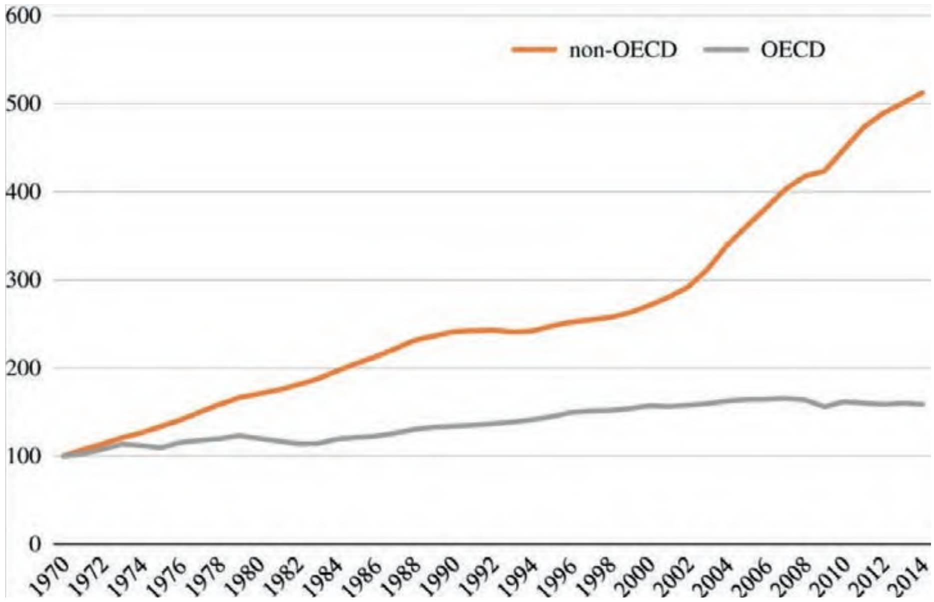


Figure A.3 OECD and non-OECD primary energy consumption, 1970–2014 (1970 = 100). Source: Van de Graaf and Colgan (2016). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

A.2.1.3 Weather

Weather variations can have a significant effect on energy demand and associated emissions, in particular how much space heating is needed. Colder winters will of course require more heating than warmer ones.

A method used to understand the impact of weather on space heating is 'degree days' (see impact on indoor comfort in Volume 3, Chapters 6 and 7). A degree day is the measure or index used to take account of the severity of the weather when looking at energy demand in terms of the heating (or cooling) load of a building. A degree day is a measure of how cold (or warm) it is outside, relative to a day on which little or no heating (or cooling) would be required. The larger the number of heating degree days, the colder the weather. For example, if the outdoor temperature throughout a particular day is on average 8°C, then this would be 10°C less than the desired indoor temperature of 18°C and would thus contribute 10 degree days.

The typical heating season in Ireland is October to May. Met Éireann calculates degree day data for each of its weather stations. Using this, SEAI then calculate a population weighted average of these data to arrive at a meaningful degree day average for Ireland that is related to the heating energy demand of the country (SEAI, 2021c).

A.2.2 Assessing energy technologies

A.2.2.1 Levelised cost of electricity or energy

A key means of comparing different technologies is the LCOE (Visser and Held, 2014; Shen et al., 2020). This is the cost at which electricity or energy must be sold for the investment in a project to breakeven. It includes both the upfront capital and operation/maintenance costs over the lifetime of the development. Usually, the LCOE is calculated over a 10–40 years lifetime of an installation and per unit of electricity generated (e.g. €/MWh). The calculation is as follows (Visser and Held, 2014)

$$\text{LCOE} = \frac{\text{Cost over lifetime ofthe project}}{\text{Total energy over lifetime of the project}} = \frac{\sum_{t=1}^{n} \frac{}{(1+\text{DR})^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+\text{DR})^t}}$$

LCOE = levelised cost of electricity or energy.
I_t = investment expenditures in the year t.
OM_t = operations and maintenance expenditures in the year t.
F_t = fuel expenditures in the year t.
E_t = electricity generation in the year t.
DR = discount rate.
n = economic lifetime of the power plant.

As we move towards renewable energy, LCOE is increasingly recognised as an incomplete measure (Shen et al., 2020; Parzen et al., 2021). It fails to take account of integration costs, time-dependent revenue opportunities (especially in the case of intermittent renewables) and relative environmental impacts (e.g. external costs) (Krey et al., 2014), as cited in (IPCC, 2022b). However, it nonetheless remains a commonly used metric for comparing different technologies and is thus referenced throughout the following sections.

A.2.2.2 Capacity factors

Renewable energy sources such as the wind and sun will not be available all the time. The availability of a resource is known as its capacity factor, which is a measure of what percentage of the hours in a year it is available.

For example, in the case of wind energy, not all of that capacity can be realised at any given time – it depends on the strength and direction of the wind on any given day, winter versus summer variations, and longer-term annual fluctuations. In addition, due to the difficulty in controlling the turbine speed, compared with conventional generators, there are some constraints and curtailment necessary to keep the grid stable (further discussed in Annex A.5). The combined effect of the above variations is summed into an annual capacity factor – the ratio between actual wind generation and the installed wind capacity. In Ireland, this typically varies between 25% and 35%. This means that in 30% of the hours in the year the wind has the right conditions to produce electricity from onshore wind.

This is most relevant for renewable electricity generation (Table A.1).

Table A.1 *Capacity factors recommended by EirGrid for the seven technology categories defined in the RESS 1*

Technology	Capacity factor
Onshore wind	35%
Offshore wind	45%
Solar	11%
Hydro	35%
Biomass HECHP	85%
Waste to energy HECHP	43%
Biogas HECHP	36%

Note: HECHP, high efficiency combined heat and power.

Source: EirGrid and SONI (2021a).

A.2.2.3 Life cycle impact of renewables and other important technologies

Another key consideration is the life cycle impact of a technology. This measures the total environmental impact of a technology over its lifetime. It can capture the emissions associated with production and operation. While manufacturing renewables results in some emissions, these are negligible compared with the savings achieved over their lifetime (Figure A.4; Roser, 2022).

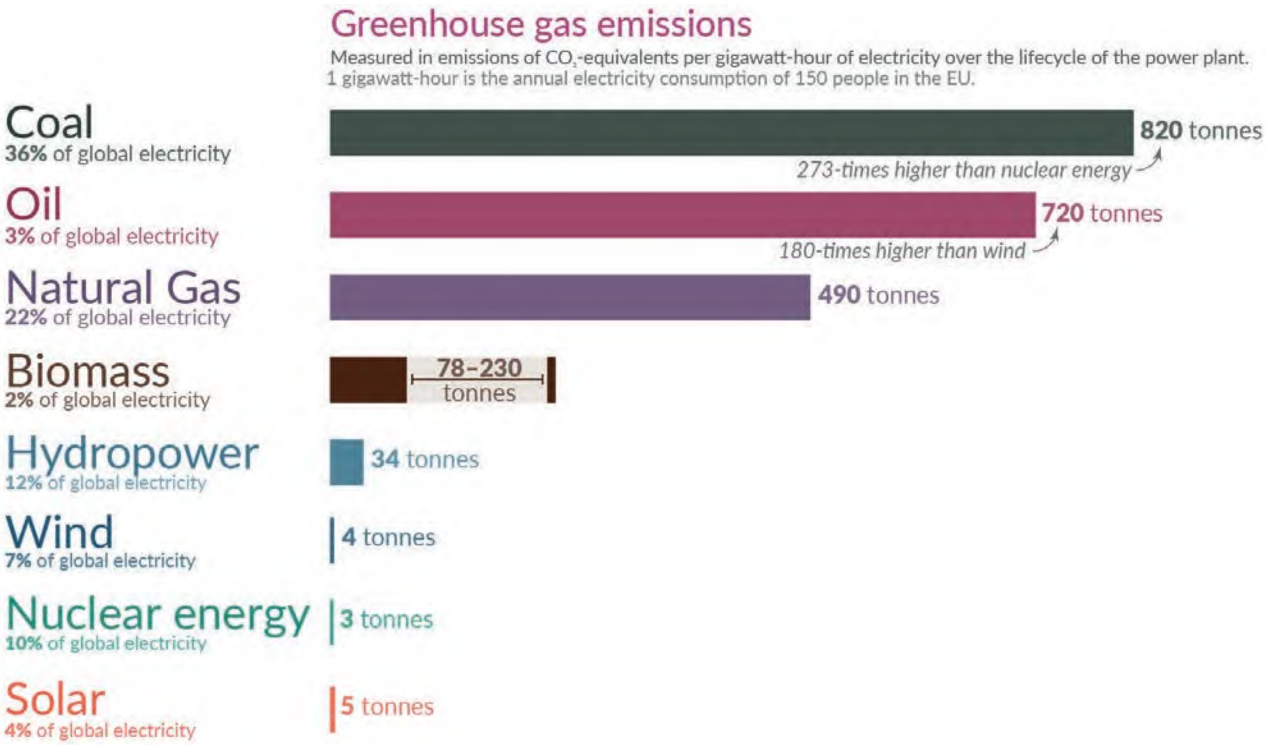


Figure A.4 Life cycle CO_2 emissions per gigawatt of electricity generated over the lifetime of a power plant. Source: Roser (2022). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

The secure supply of many metals and minerals (e.g. cobalt, copper, lithium and rare Earth elements) is critical to technologies like wind turbines, PV cells and batteries. Reliance on these minerals has raised questions about possible constraints to decarbonisation. However, the name of these metals is a misdirection as they are in fact abundant (Abraham, 2015). The classification as rare Earth is more to do with the complicated extraction process. It is really a question of having enough, but the pace at which we can produce the necessary technologies and at what price. Another concern is the mining impacts (both environmental and social), which are challenging to measure because it is difficult to follow the process from mine to final product.

Ireland has a diverse geology and a range of rich mineral deposits, including zinc, lead, copper and gold-bearing quartz veins. Recent exploration has also been carried out for platinum-group minerals, rare Earth elements, technology metals (e.g. lithium, tantalum, tungsten and tin), nickel and chromite, diamonds and other gem minerals. There is also significant potential across Ireland for industrial minerals. In recent years, gypsum, dolomite, silica sand, brick shale and fireclay have all been mined.

The end of life for wind turbine blades is an emergent issue. Wind turbine blades have a lifetime of about 20 years and are made from complex composites, and so it is difficult to reclaim the materials. The Re-Wind project in Ireland looks at potential use cases for the blades (Deeney et al., 2021). Nagle et al. (2022) warn that by 2040 Ireland could have 53,000 tonnes of blade waste from onshore wind farms, and highlight that repurposing is the preferred option over recycling because it is less resource intensive. The options investigated to date by Irish research primary look at the use of repurposed blades as structural beams in roofs (Gentry et al., 2020) or bridges (Leahy et al., 2021; Ruane et al., 2022). Other partners in the Re-Wind Network have looked at transmission towers, playgrounds, bicycle shelters and furniture (Nagle et al., 2022).

However, not all blades will be able to be repurposed and there will need to be some processing (Nagle et al., 2020). Delaney et al. (2021) conducted a spatial mapping of wind turbines to inform waste management strategies and minimise transport from wind farms to processing sites.

A.2.2.4 Forecasting technology deployment

The cost of renewables and other key technologies like batteries has fallen dramatically since 2000. The rate of deployment has continuously outperformed forecasts.

A.2.3 What are fossil fuels?

Fossil fuels found in the Earth's crust are made from decomposed plants and animals, and are formed by natural processes over millions of years. Also known as hydrocarbons, they contain the elements hydrogen and carbon in different ratios, with some impurities. They range from gases with low carbon-to-hydrogen ratios (natural gas), to liquids that contain more carbon relative to hydrogen (crude oil), to solids that are almost pure carbon (coal). This is why coal, for example, releases more CO_2 when burned than natural gas (Table A.2). Peat (turf) shares many characteristics with fossil fuels and can be thought of as immature coal where either the time or conditions required to condense the material have been insufficient. Many of the fuels we are familiar with, such as petrol, diesel and kerosene, are made by refining crude oil, the thick black substance pumped from the ground. Fossil fuels are non-renewable as the timescales required for them to form is so vast.

Fuel	gCO_2/kWh
Oil	
Diesel	263.9
Petrol	251.9
Kerosene	257
LPG	229.3
Solid fuel	
Coal	340.6
Milled peat	418.1
Sod peat	374.4
Peat briquettes	355.9
Natural gas*	202.2

Note: *2020 figure. With injection of biogas into the grid, this value is expected to gradually decrease (section 4.5.2).

Source: SEAI (2022f).

Fossil fuels have four useful properties. First, they are relatively abundant. A study in 2015 estimated that known fossil fuel reserves contained just over 10 times the amount of carbon that could be emitted to stay below 2 warming (Jakob and Hilaire, 2015). Second, they are very low cost thanks to centuries of investment in technology development and a range of government subsidies. However, it is important to note that the low cost does not reflect the environmental cost (i.e. climate change), and renewables (solar/wind) are now lower in cost. Third, and most importantly, fossil fuels are very energy dense. This means that a lot of work can be done with a relatively small amount fuel. Fourth, they are easily stored thanks to their properties and modern technology.

The energy in fossil fuels is released when they are burned in the presence of oxygen. In doing so, the stored chemical energy is converted into useful heat energy, which can be used for heat, to drive an engine or power an electricity generator. However, as the burning process is not be 100% efficient, the remaining unburned parts of the fuel are emitted in the form of the CO_2 along with other pollutants, such as sulphates and $_{PM2.5/10}$.

Fossil fuel extraction also causes the release of natural gas found alongside coal and crude oil, and through leaks in natural gas infrastructure. Natural gas is composed mainly of CH_4, which is itself a powerful GHG (Volume 1). Capturing 100%

of this is very difficult and hence, even if the CO_2 released when burned is all captured, which is also very difficult, fossil fuels would still have a substantial climate impact.

A.2.4 What is green hydrogen?

Five shades of hydrogen

Green	Blue	Turquoise	Grey	Brown
Electricity from renewable sources is used to electrolyse water H_2O and seperate the hydrogen H_2 and oxygen O	Produced using natural gas via "steam reformation"; most of the greenhouse gas emissions are captured and stored	Porduced using natural gas vie "pyrolisis", by separating methane into hydrogen H_2 and solid carbon dioxide CO_2	Porduced using natural gas via "steam reformation", but with no carbon capture and storage	Produced using coal instead of natural gas, but with no carbon capture and storage; this remains the cheapest form

Traditionally, hydrogen has been produced via the steam methane reforming of natural gas, a process that releases substantial volumes of CO_2, but this process can also be paired with CCS systems, which sequester the resulting emissions (Budinis et al., 2016). Such storage involves considerable logistic and economic challenges (Vinca et al., 2018). An emerging alternative is methane pyrolysis, a process in which natural gas is decomposed into hydrogen and easily storable solid carbon (Gray et al., 2021). The hydrogen produced using fossil fuels and CCS is often referred to as 'blue hydrogen' (IEA, 2019). Because natural gas is an inexpensive feedstock (SEAI, n.d.), both steam methane reforming with CCS and methane pyrolysis can be used to produce blue hydrogen at relatively low cost (Collodi et al., 2017; Parkinson et al., 2017). However, both technologies have carbon capture rates of less than 100% (IEA, 2019) and suffer from fugitive emissions of CH_4, which is one of the most potent GHGs (Balcombe et al., 2017). Without additional measures, these processes are neither carbon-neutral nor net zero compatible, and are thus not viable hydrogen production mechanisms (IRENA, 2020b).

Electrolysis, by contrast, is a more sustainable process that uses electric current to split water into hydrogen and oxygen. When renewable electricity is used, the resulting product is termed 'green hydrogen' to signify that it is climate friendly (IEA, 2019). Electrolysis can be used to convert renewable electricity into hydrogen, is highly scalable and could be used to meet the increasing demand for dispatchable low-carbon fuel in a future energy system (IEA, 2021b). As the technology develops and its decarbonisation potential is increasingly recognised, there is also scope for further technology-driven improvements in the performance and cost of electrolysis systems (IRENA, 2020b). These systems also have the advantage of greatly simplifying life cycle assessment studies: as long as the electricity is obtained from a renewable source, the resulting hydrogen fuel is zero carbon (European Union, 2018).

> *"Electrolysis can be used to convert renewable electricity into hydrogen, is highly scalable and could be used to meet the increasing demand for dispatchable low-carbon fuel in a future energy system (IEA, 2021b)"*

A.3 Overview of Irish Analysis, Models and Tools

Energy system models provide a critical evidence base for decarbonisation policies in Ireland, the EU and globally. These integrated whole energy systems models have a number of advantages over single-sector or static approaches. They bring together the complex dynamics (incorporating technologies, fuel prices, infrastructures and capacity constraints) of the entire energy system (Balyk et al., 2022). A key strength is to approach energy as a system rather than as a set of discrete non-interactive elements. This has the advantage of providing insights into the how different sectors interact, which cannot be understood when analysing a single technology, fuel or sector. For example, a single focus on the electricity sector risks excluding changes in electricity demand driven by the electrification of transport and heating. It is only by examining all sources of emissions together that we can understand the cumulative GHG emissions associated with different mitigation pathways.

A.3.1 Development of Irish TIMES model

In Ireland, a commonly utilised tool to look at future low-carbon energy systems is the Irish TIMES energy systems model (first generation) or TIMES Ireland model (second generation). The EPA and the SEAI have funded the development of the Irish TIMES model since 2009. It has a long (more than 10 years) history of providing analytical input to Irish energy policy development (Ó Gallachóir et al., 2020). This includes acting as the basis for Ireland's first low-carbon roadmap in 2015 (Deane et al., 2013; Department of Communications, Energy and Natural Resources, 2015) and Ireland's first national mitigation plan in 2017 (Department of Communications, Climate Action and Environment, 2017), and more recently, as discussed in section 2.4, the TIMES Ireland model provided important analysis that informed the first two carbon budgets (Climate Change Advisory Council, 2021).

The TIMES models produce pathways for Ireland consistent with either a carbon budget or a decarbonisation target. It is an optimisation model, which means that it calculates the lowest-cost configuration that can meet future projections of energy demand, while respecting technical, environmental, economic, social and policy constraints. Key inputs and constraints include energy resource availability and costs for different technologies, the technical and cost evolution of new mitigation options, and maximum feasible uptake rates of new technologies. Alternatively, TIMES can be used to assess the implications of certain policies, namely regulatory or technology target setting (e.g. Biofuels Obligation Scheme or the sales/stock share target for EVs). For a detailed technical description of how the various sectors are constructed in the TIMES Ireland model, see Balyk et al. (2022).

In its original incarnation, the Irish TIMES model operated as a component of the Pan European TIMES (PET36) project, which included datasets for the 27 EU Member States, Iceland, Norway, Switzerland and the Balkan countries. The Irish TIMES model dataset was extracted, updated with local detailed data and recent macroeconomic projections, calibrated to the national energy system, scrutinised to assure confidence in model assumptions and peer reviewed. This work was carried out by the Energy Policy and Modelling Group at the University College Cork, with macroeconomic projections provided by ESRI. Model calibration runs were carried out to ensure smooth model dynamics, within a range of acceptable rates of change across public policy and private stakeholder expectations. The original Irish TIMES model was developed with a remit to project national energy consumption and GHG emissions to inform national policy decisions (Ó Gallachóir et al., 2012).

Emissions reduction targets out to 2050 were investigated by Chiodi et al. (2013) using a techno-economic energy model of Ireland. The model showed that GHG emission reductions of between 80% and 95% can technically be achieved. A 50% emissions cut in agriculture was required to achieve 95% reductions from the energy system. The additional cost to achieve mitigation remains less than 2% of GDP levels in 2050 for the scenarios examined. Scenarios have been developed to the medium term (2020) and long term (2050), investigating the energy system required to meet EU renewable energy targets and emissions reductions targets (Chiodi, 2014). Chiodi et al. (2016) extended the Irish TIMEs energy system model to include non-energy emissions from agriculture to provide richer insights into the dynamics and interactions between the two (e.g. in competition for land use); however, no net zero results were produced.

The role of bioenergy in Ireland's long-term energy scenarios was first explored by Chiodi et al. (2015), using the Irish TIMES energy system model. An 80% reduction in CO_2 emissions was assessed and the results pointed to the need for bioenergy to meet this target, with pathways and costs impacted by sustainability criteria and limitations on bioenergy imports, namely the increased use of indigenous bioenergy feedstocks, increased electrification in the energy system, the introduction of hydrogen and higher marginal abatement costs. Czyrnek-Delêtre et al. (2016) used the Irish TIMES energy systems to assess the impact of a range of land use change emissions' levels on the evolution of Ireland's low-carbon energy system. A reference scenario was developed where land use change is ignored, and Ireland achieves a least-cost low-carbon energy system by 2050. If high indirect land use change emissions are included, then this results in a 30% decrease in bioenergy and a 68 % increase in marginal abatement costs by 2050. Hydrogen is used instead of bioenergy in the freight sector in this scenario, while private cars are fuelled by renewable electricity. If GHG emissions from indirect land use change were considered less severe, then indigenous grass biomethane becomes the key biofuel, representing 31% of total bioenergy consumption.

In recent years, Ireland and Europe's climate ambition have dramatically increased with pledges for net zero emissions (section 2.1). To be able to provide answers to the more challenging questions associated with deep decarbonisation, the Irish TIMES model has been updated and was renamed TIMES Ireland model (Balyk et al., 2022) (Figure A.5).

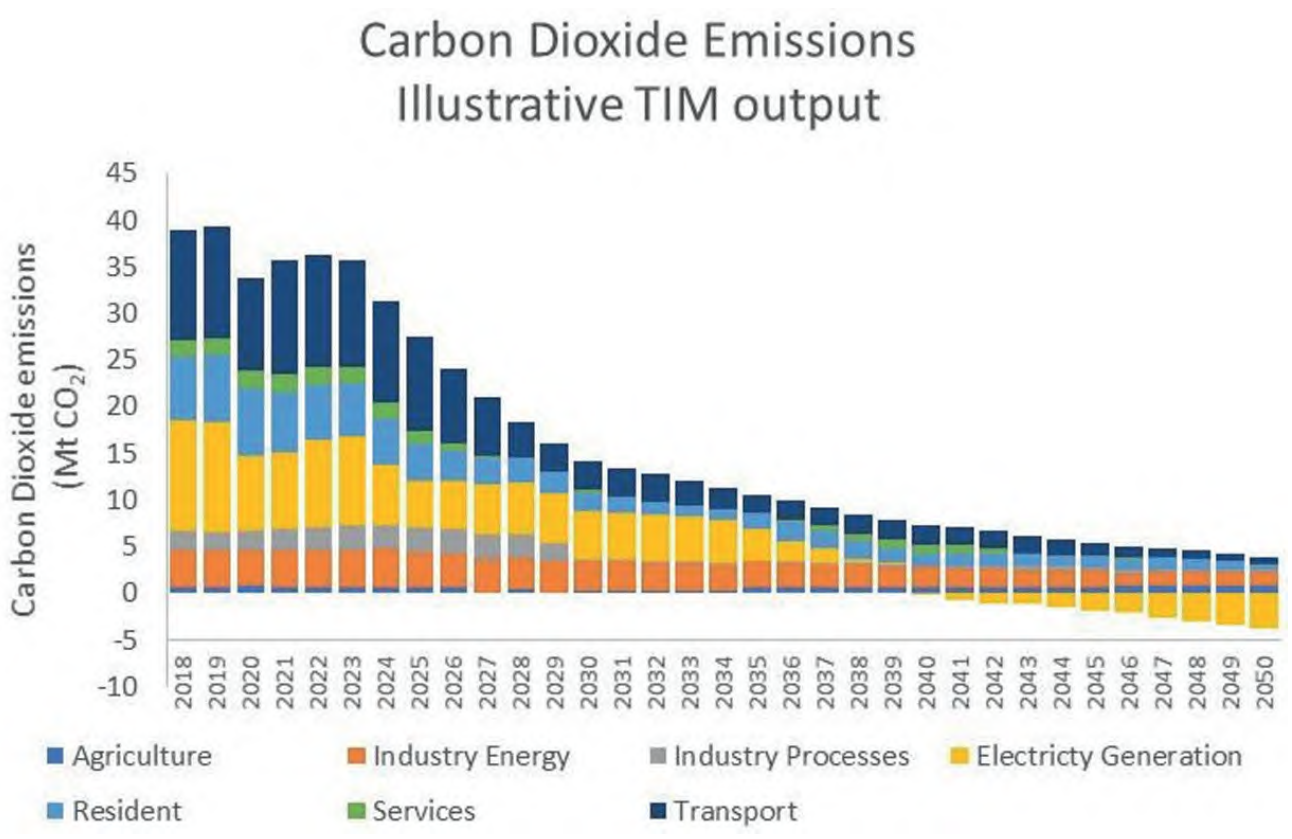


Figure A.5 Example of an emissions reduction and removals deployment pathway for 2018–2050 from the Times Ireland model. Source: Climate Change Advisory Council (2021).

Studies utilising this new iteration of the model are only just starting to emerge. Aryanpur et al. (2022) modelled scenarios for passenger travel in 2030, while Gaur et al. (2022a) looked at low energy demand scenarios in 2050, and both provide important insights for the remainder of this annex. The priority list for future development outlined by Balyk et al. (2022) is:

- modelling gas supply at hourly resolution (it is currently modelled at a seasonal level, which may unintentionally allow for energy storage capacity);
- modelling electricity interconnectors with the UK and France at the same time resolution as the power sector, taking into account capacity constraints on top of annual trade constraints;
- modelling hydrogen production routes other than from renewables (green hydrogen), such as blue, brown and grey hydrogen production options;
- reviewing and updating bioenergy conversion options, including an update of domestic bioenergy potentials;
- reviewing and updating future low-carbon technology costs;
- developing further the agri-TIMES module, first developed by Chiodi et al. (2016), to better represent agriculture, livestock and land use emissions and mitigation options, including competition for land use;
- developing a more detailed bottom-up focus on the industry sector, which is currently modelled in an aggregated top-down fashion, and a disaggregation of the services sector;

- developing a 'business as usual' or 'with existing policy measures' case, which includes current policies, measures and hurdle rates to represent end-use technology uptake.

A.3.2 Low Emissions Analysis Platform

Another commonly used model is the LEAP: Low Emissions Analysis Platform(LEAP) (Heaps, 2012). Unlike TIMES, LEAP is a simulation-based model, which means that it relies on user inputs for scenario outcomes. This makes it more suited to answer questions on the impact of particular policy measures, such as the targets set for the number of EVs or home retrofitting.

The LEAP GHG Ireland Analytical Tool for 2050 was developed through EPA research funding (Mac Uidhir et al., 2020b). It provides a reference scenario of projected energy demand and supply to 2050 based on current trends, and a number of mitigation scenarios for 2030 based on the Climate Action Plan 2019. This original iteration was developed before the CSO released the 'Business Energy Use Survey' and so it has limited details of the industry and commercial sectors (as discussed in section 5.2.2), highlighting the importance of continued model development. It has primarily been used to assess options to decarbonise the residential and transport sectors.

Similar to the case of TIMES, studies are only just starting to emerge and have to date been focused on scenarios for 2030, as opposed to 2050. Mac Uidhir et al. (2022) look at the ambitious EVs and retrofitting targets in the Climate Action Plan 2021, but this was only out to 2030. They highlight the scale of the challenge and the unprecedented diffusion required to meet the 2030 targets. For EVs, following the most successful EV diffusion example (Norway) would deliver 200,000 EVs (only 23% of the Climate Action Plan 2021 target). McGookin et al. (2022) developed a LEAP model of the Dingle Peninsula, which looked at scenarios to 2030, informed by an extensive community engagement process. They highlight heating and private car travel as key priorities for rural areas.

A.3.3 GHG-WE tool

The GHG-WE tool is an open-source model of society-wide GHG emissions, with a specific focus on the impact of different GWP metrics (McMullin and Price, 2020a, 2020b). GHG-WE is a spreadsheet-based tool, which incorporates the recently developed GWP* metric to aggregate short-lived CH_4 with long-lived CO_2 and N_2O, to enable a cumulative CO_2-we comparison of policy scenarios. The purpose of the tool is to assess trade-offs between energy and non-energy emissions.

Using the tool, six illustrative scenarios were examined (McMullin and Price, 2020b). The five mitigation scenarios cover variations on CO_2 and non-CO_2 emissions:

- CO_2 net zero in 2050 (cn2050) or 2040 (cn2040);
- CH_4 and N_2O annual emission rates stay flat (MN_FLAT) or are each cut linearly by –25% (relative to 2019) from 2020 to 2050 (MN-25%) or by –50% (relative to 2019) from 2020 to 2050 (MN-50%); thereafter they remain flat at these lower levels.

These scenarios provide pathways to net zero for the gases, an assessment of the extent to which Ireland may overshoot its carbon budget and subsequently the cumulative CDR required (Table A.3). A key finding was that the required levels of cumulative CDR, in all bar the MN-50%_Cn2040 scenario, significantly exceed the upper limit of 200MtCO_2 determined by (McMullin et al., 2020b).

Table A.3 *GHG-We tool: key figures in scenarios*

Scenario	Net zero GHGs year	Net CO_2 2015–2050 (MtCO_2)	Net CH_4 2015–2050 (MtCO_2-eq)	Net N_2O + CH_4 2015–2100 (MtCO_2-we)	CDR 2015–2100 (MtCO_2)
MN_FLAT_Cn2050	2058	990	591	1,020	1,466
MN-25%_Cn2050	2049	990	515	470	915
MN-50%_Cn2050	2041	990	439	–70	361
MN-25%_Cn2040	2040	660	515	470	590
MN-50%_Cn2040	2036	660	439	–70	35

Source: McMullin and Price (2020b).

While this shows potential trajectories for the key GHG emissions, the lack of sectoral details (i.e. what is currently driving emissions and options to reduce them) means that it does not provide clear mitigation pathways. It has a very simple representation of CO_2 emissions as a single net value without disaggregation among sources (i.e. fossil fuels, industry or land use CO_2) or sinks (land use or technological CO_2). The need for energy system disaggregation (as provided by TIMES, Annex A.3.1, or LEAP, Annex A.3.2) is noted as an important area for future development.

A.3.4 Agriculture, forestry and other land use models

Globally, the AFOLU sector is a major source as well as a sink due to agricultural production and LULUCF activities. However, there are considerable institutional, policy coordination and implementation issues that obstruct mitigation potential of this sector. There is a lack of clarity in this sector with regard to aims in achieving climate neutrality via sustainable food production and delivering services underpinning effective climate action (Duffy et al., 2022b). Recently, the European Commission have proposed using models for the AFOLU sector post 2030 as a part of 'Fit for 55' package (Haughey et al., 2023). When we combine agriculture and LULUCF in Ireland it is particularly challenging because they are both sources (unlike the average picture in the EU where LULUCF usually off-sets some of the agri-activity emissions).

Several models have been developed in Ireland, keeping in view the high agricultural emissions associated with this country. For example, Chiodi et al. (2016) integrated agricultural and energy system modelling, providing insights into the dynamics and interactions between the two systems (e.g. in competition for land use). This resulted in a reduction of only about 20% of emissions (relative to 1990) and the bulk reductions would be required from the energy sector. The possibility of achieving at least 80–95% of reductions would be challenging without significant reduction in agricultural activity levels.

Current modelling of agriculture and associated emissions in Ireland has been carried out using a top-down sector/market-based FAPRI-Ireland model and a bottom-up farm-level agricultural greenhouse gases simulation. The latter is a farm-level modelling tool developed from the Teagasc National Farm Survey (Hennessy et al., 2011) These models comprehensively aim at incorporating livestock, crops and forestry based on production consumption, trade and policy measures affecting the overall sector. The FAPRI-Ireland model can provide valuable insights into the potential impacts of policy changes on the Irish agricultural sector and the broader economy, including under the neutral pathway scenarios (Donnellan and Hanrahan, 2006; Schulte et al., 2013). This model has also been used as a baseline for development of the MACC for agriculture 2021–2030 (section 6.1.1) (Teagasc, 2018; Lanigan et al., 2019). Mitigation reforms from this analysis could reduce emissions by 1.85MtCO_2-eq per annum between 2021 and 2030, and potential sequestration of 2.97MtCO_2-eq per annum between 2021 and 2030.

The EPA-funded *Climate Change and Land Use in Ireland review* (Haughey, 2021), drawing on from the findings of the special report on climate change and land (Mbow et al., 2017), investigated the potential of 40 integrated approaches (highlighting the potential for co-benefits and trade-offs) towards climate mitigation and adaptation for Ireland. Among the 40 approaches, 12 were found to be under 'high potential applicability', or in other terms have a positive impact on climate mitigation as well as adaptation and can help in significantly reducing potential emissions from the sector. At a consumer level, changes in dietary preferences and reducing food wastes were found to be optimal conditions. At the agriculture land management level, increased food productivity, improved grazing management, agroforestry, agricultural diversification, improved soil management, peatland management and biodiversity conservation were all found to beneficial. More information on these options is provided in Table A.4.

Table A.4 *Integrated response options assessed to have highest applicability for positive outcomes in both climate mitigation and adaptation within AFOLU. Source: Haughey (2021)*

Response option category	Response option	Notes/caveats
Demand management	Dietary change	Current deployment levels are not known. There are boundary issues with regard to exported and imported food and the associated production emissions
	Reduced food waste	National initiatives are under way, but food waste remains high
Agricultural land management	Increased food productivity	There are existing national research initiatives targeted at increased agricultural efficiency. There is a risk of rebound effects
	Improved grazing land management	There are significant opportunities for climate mitigation and adaptation, as this grazing is the largest type of national land use
	Improved livestock management	Can improve economic and environmental sustainability of livestock production. Actions under this option are efficiency based and associated with a high risk of rebound effects
	Agroforestry	Strong potential to achieve mitigation and adaption goals with benefits for rural livelihood diversification. Current low levels of deployment indicate significant challenges to increase uptake by farmers
	Agricultural diversification	Low levels of deployment currently indicate a significant knowledge transfer challenge
Land management for CO_2 removal	Bioenergy and BECCS	Could make a significant contribution to climate mitigation but current low levels of deployment require coordinated actions. Sustainable deployment is required otherwise this option could negatively impact biodiversity and increase demand for land
Forest management	Afforestation	Sustainable deployment and forestry management required or can negatively impact biodiversity. Could increase competition for land and may face significant social resistance
Other ecosystems land management	Reduced pollution including acidification	Significant co-benefits for air and water quality, biodiversity conservation and reducing land degradation
	Restoration and reduced conversion of peatlands	Major potential to reduce GHG emissions and create carbon sinks in degraded peatlands and organic soils under agriculture
	Biodiversity conservation	Would benefit from more integration with climate change mitigation and adaption policies. Land-based mitigation options could pose a threat to biodiversity conservation

The potential of replacing livestock emissions in Ireland with afforestation-led carbon sequestration was analysed via a hypothetical national planting scenario by Duffy et al. (2020b). From the results, the highest sequestration potential is plausible from replacing dairy farms with forests, this is due to the high emissions from dairy and greater sequestration potential obtained from higher-yielding forests planted on better-quality soils associated with dairy production. The results also mentions that afforestation of 100,000Ha of dairy and beef cattle and sheep could potentially abate 13.91MtCO_2-eq after 10 years, and 150.14MtCO_2-eq (unthinned plantations) or 125.89MtCO_2-eq (thinned plantations) over the course of the rotation.

The EPA-funded SeQUEsTER (Scenarios Quantifying land Use & Emissions Transitions towards Equilibrium with Removals) project aims at bioeconomic modelling life cycle analysis assessments to identify pathways towards net zero GHG emissions in Ireland's AFOLU sectors. The result of this project is represented in the GOBLIN model developed by Duffy et al., 2022b; the model is a biophysical one capable of identifying broad pathways towards 'net zero' in Ireland's AFLOU sector. The sectors within AFLOU are classified as net sources or sinks based on a national inventory report (EPA, 2021a) for CO_2 fluxes to and from mineral (soil organic carbon) and organic soils, forestry and croplands. Figure A.6 shows an approximate estimate of emissions from agriculture, organic soils and wetlands, and the offsetting potential of the forestry sector to achieve climate neutrality.

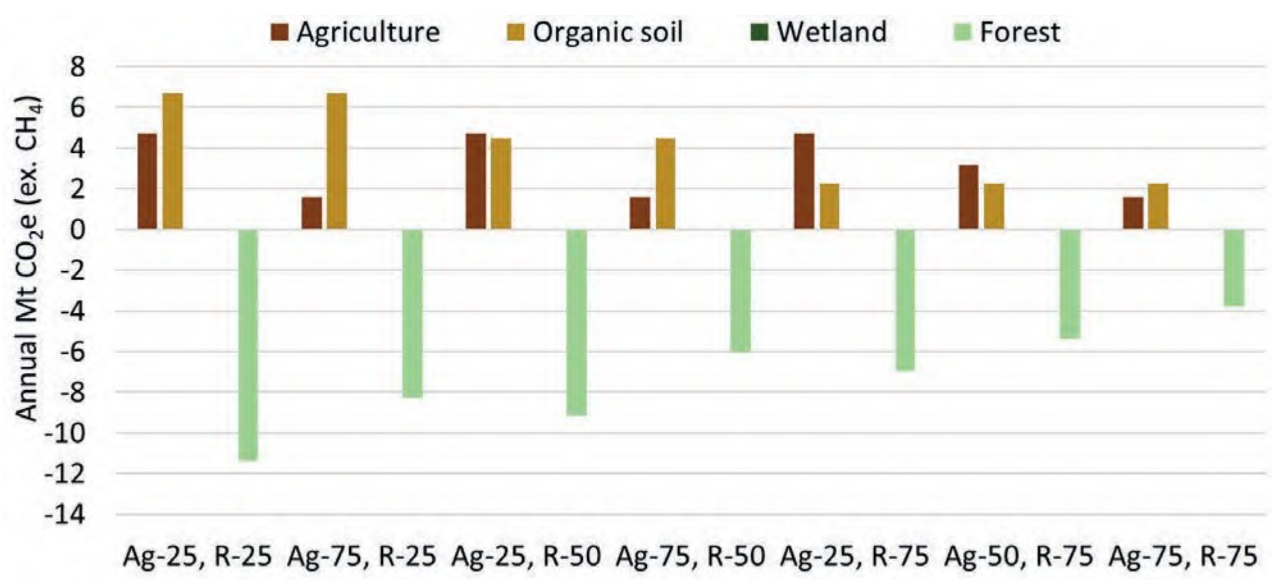


Figure A.6 Combinations of approaches across agriculture, organic soils under grass, wetlands and forestry for achieving climate neutrality in 2050 in the AFOLU sector. Source: Styles and Duffy (2023).

Key results from the study were categorised on the basis of achieving a net zero in AFLOU (N-Z-AFLOU) scenario and a national neutrality (N-Z-National) scenario, where emissions exceed AFOLU neutrality by a margin that is sufficient to offset 5–10% of non-AFOLU national emissions in 2020 (Duffy et al., 2022a). Among the 850 scenarios analysed in the project (2015 data were used as baseline), 146 met the N-Z-AFLOU scenario and 38 the N-Z-National scenario. The mean reductions in dairy and beef herds were 42% and 52% for N-Z-AFLOU and N-Z-National, respectively. The spared land generated from the herd reductions allowed for additional afforestation in the N-Z-AFLOU and N-Z-National scenarios. However, achievement of climate neutrality could incur substantial trade-offs with respect the national agricultural production. For example, in a scenario (N-Z-AFLOU) where highest milk production is achieved (over 87% of 2015), the simultaneous beef sector would account for only 21% of 2015 beef production. Similarly, the maximum beef production in the N-Z-AFOLU group is just 49% of 2015 production, with 58% of milk production in same scenario. The maximum production levels for the N-Z-Natural scenario were 66% of 2015 production for milk coupled with 20% for beef. Relative to the baseline year of 2015, CH_4 emissions due to enteric fermentation and manure management were reduced by 37% and 38%, respectively.

With regard to re-wetting previously drained organic soils, the N-Z-AFLOU and N-Z-National scenarios resulted in a potential to sequester 5.2TgCO_2-eq and 5.5TgCO_2-eq, respectively. It was also noted that for the various net zero scenarios presented in this study, the average sequestration of forests increased by 147%, while grass land emissions reduced by 87%.

Conclusions from this model is that afforestation stands out as the most important driver in achieving the net zero balance, and also that reduction in herd numbers without appropriate use of spared land for carbon capture (especially afforestation) could result is higher penalties within the food production systems.

An EPA report by Haughey et al. (2023) investigated various land use scenarios and their capacity to facilitate net zero GHG emissions in Ireland by 2050. The models were developed from integrated approaches for AFOLU developed by Haughey (2021) and baseline data were obtained from Duffy et al. (2022a). The abatement measures for a net zero pathway were considered alone or in combination, and the possible co-benefits of implementation were also examined (Haughey et al., 2023). A key point to be noted from this model was that only when all the measures mentioned below were combined was a net zero target met.

- 875,000ha of additional forestry by 2050 (rate of 35,000hayr^{-1}) coming from the grassland category;
- 302,000ha of grassland on organic soils re-wetted successfully (which is estimated as 90% of that category of current land use);
- 70,000ha of exploited peatland re-wetted successfully (which is estimated as 100% of that category of current land use);
- a 30% increase in grassland livestock production efficiency and a 30% decrease in grassland livestock numbers;
- 420,000ha space for nature coming from grassland by 2050 (equivalent to 10% of the total grassland area in 2018);
- 420,000ha bioenergy from grassland by 2050 (equivalent to 10% of the total grassland area in 2018);
- 420,000ha cropland from grassland by 2050 (equivalent to 10% of the total grassland area in 2018).

It must be taken into account that the last three points are add-on features, and it was not possible to reach net zero where the conversion to cropland took place.

A.3.5 Other analysis and tools

A 100% renewable energy system was investigated by Connolly et al. (2011) using the EnergyPLAN model. It was shown that an Irish energy system with district heating, heat pumps and a transportation mix of electricity, hydrogen and biomass is the most efficient and resource-friendly method of converting Ireland to a 100% renewable energy system. It was assumed that energy demands would remain the same as 2007, which is unlikely the case, and the system was not constrained by carbon budgets.

Decarbonisation opportunities using MACCs for the Irish energy system were presented by Yue et al. (2020b), looking at the cost associated with net zero emissions under different technology constraints. The Climate Action Plan 2019 was informed by a MACC prepared for the Department of Communications, Climate Action and Environment by McKinsey (Department of Communications, Climate Action and Environment, 2019). McKinsey also provided sectoral modelling for the Climate Action Plan 2023, but there are very little details on the underlying model in the published summary of this analysis (Department of the Environment, Climate and Communications, 2023) (Figure A.7).

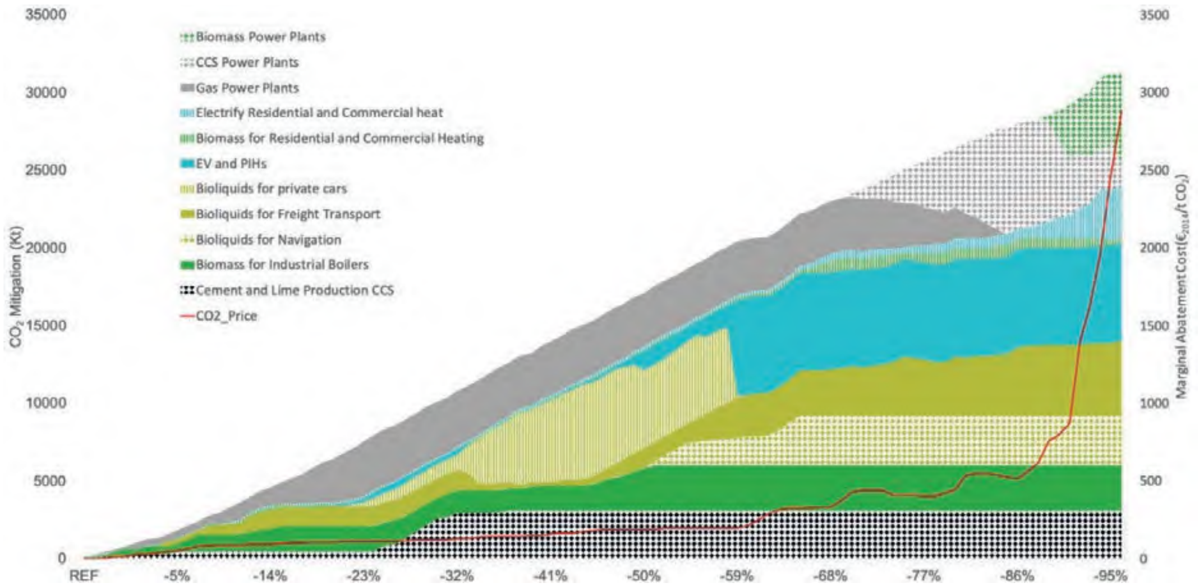


Figure A.7 Example of a MACC for Ireland in 2050 at different levels of mitigation ambition. Source: Ó Gallachóir et al. (2020).

The Irish power system as part of the wider EU decarbonised power system was examined by Gaffney et al. (2020). This analysis compares the impacts of high levels of renewable electricity and negative emissions technologies on exploratory visions of the future EU power system (2050) in terms of emissions reduction, technical operation and total system costs. The analysis shows that high renewable power system scenarios coupled with low levels of negative emissions technologies, such as biomass CCS (< 2% of installed capacity), can deliver a net-negative European power system at lower comparable cost without breaching published sustainable biomass potentials in Europe (or requiring imports) or geological storage potentials, while also contributing to power system inertia.

In an industry-funded study, Deane et al. (2021b) examined one pathway to a net zero energy system consistent with a 376Mt carbon budget applied from 2020. It was found that the system was technically feasible, but challenging. Significant investment must be made to achieve this, and because these investments are paid back over decades the investments as a percentage of GDP for a net zero energy system is relatively low. It was calculated that the additional incremental investment in 2050 over the current level of climate ambition of an 80% reduction in CO_2 is approximately 1.4% of GDP.

ESRI developed the I3E (Ireland Environment, Energy and Economy) model. This is a top-down computable general equilibrium model, which seeks to reproduce the structure of the economy (de Bruin and Yakut, 2021). In addition to monetary flows between sectors, it contains a set of fuels (e.g. kerosene, diesel, coal), which production activities will seek to run on the cheapest available. For example, when an energy policy is implemented, such as an increase in carbon tax, production sectors will substitute energy inputs for other inputs and/or decrease the carbon content of their energy inputs by demanding cleaner energy. Reports from ESRI have used the I3E model to look at the impact of carbon tax (de Bruin and

Yakut, 2019), regional labour impacts of the transition to a low-carbon economy (de Bruin et al., 2019c), and the effects of eliminating Irish government fossil fuel subsidies on the Irish economy (de Bruin et al., 2019c).

A number of roadmaps to 2050 were produced by SEAI, examining the role of future development of wind energy (SEAI, 2011b), ocean energy (European Ocean Energy Association, 2010) and smart grids (SEAI, 2011a). They assumed an overall annual electrical final energy demand in excess of 48,000GWh by 2050, with a corresponding peak demand of 9GW. Onshore wind generation will be able to supply up to 33,000GWh of the total demand. The wind industry was expected to hit a peak annual investment of between €6 billion and €12 billion by 2040. Wind has a cumulative investment potential of €100–200 billion in 2050. More recently, the national heat study provided a number of scenarios for net zero heat by 2050 (SEAI, 2022k). It found that pathways with higher levels of electrification had lower cumulative emissions than those that relied on hydrogen injection into the gas grid, and that district heating could play a key part, with potential to cover 50% of building heat demand. These pathways were developed using SEAI's National Energy Modelling Framework, which is a full energy economy model that is linked to ESRI's I3E model (SEAI, 2022m).

A.3.6 Current debates and priority areas in model development

The models and tools outlined in the previous subsections are just a small sample from what is a very large range of climate and energy system modelling tools available for different applications across geographic and technical scales, as demonstrated by the many reviews conducted on the topic: Connolly et al. (2010), Foley et al. (2010), Banos et al. (2011), Suganthi and Samuel (2012), Sinha and Chandel (2014), Allegrini et al. (2015) and Ringkjøb et al. (2018). They are important tools for us to understand current sources of GHG emissions and options to reduce them in the future. At global (section 1.2.3), EU and national levels, these computer models provide a critical evidence base for policy. However, they are not without issues. As quantitative tools, they rely on overly simplistic representations of society, which is a highly complex and dynamic system. The key areas of improvement identified by international and Irish literature are outlined in Table A.5.

Table A.5 *Summary of research priorities in the development of energy system models*

Reference	Issue	Description
Collins et al. (2017), Lopion et al. (2018), Weinand et al. (2019), Prina et al. (2020), Aryanpur et al. (2021)	Temporal and spatial resolution	National models rely on poorly disaggregated spatial data for key variables like renewable energy potentials and system costs. Similarly, time horizons are very long, spanning decades, and thus often rely on simplified representations of power system variations across years, seasons, days, etc.
Coelho et al. (2018), McGookin et al. (2021a)	Data availability	Datasets are often inaccurate, incomplete or unavailable
DeCarolis et al. (2017), Pfenninger (2017), Pfenninger et al. (2017, 2018), Weinand et al. (2020)	Transparency and open source	The model building process requires significant modeller judgment with limited standard guidance, and underlying assumptions are often hidden
Pye et al. (2018), Wiese et al. (2018), Yue et al. (2018a)	Dealing with complexity and uncertainty	There is huge uncertainty around model parameters, such as future technology cost or deployment rates
Creutzig et al. (2018), Pye et al. (2021)	Focus on supply-side measures	Models predominantly project historical trends based on GDP growth and thus potential demand-side measures, such as a reduction in energy demand, are often absent from analysis. This contributes to a reliance on technologies like CO_2 removal
Li et al. (2015), Geels et al. (2016), McDowall and Geels (2017), Nikas et al. (2020)	Techno-economic modelling limitations	Models need to look beyond techno-economic representations of the energy system and incorporate real-world behaviour insights. However, complex/dynamic social and political systems are not easily quantifiable
Sharma et al. (2020), Xexakis et al. (2020), McGookin et al. (2021b)	Participatory/ transdisciplinary approaches	Stakeholder and public perspectives and preferences should be integrated into the modelling process

A.4 Blue Carbon

Of all the green carbon captured annually in the world, that is the carbon captured by photosynthetic activity, over half (55%) is captured by marine organisms (Nellemann et al., 2009). Blue carbon emerged as a concept in 2009, stemming back to reports by the United Nations Environment Programme and the International Union for Conservation of Nature that described the carbon that is captured and stored by oceans and, in particular, the carbon stored by vegetated coastal habitats (Cott et al., 2021). Oceans and coastal marine systems play a significant role in the global carbon cycle. Some 93% of the Earth's CO_2 (40Tt) is stored and cycled through the oceans (Nellemann et al., 2009; Cott et al., 2021). At a global level, blue carbon ecosystems (mangrove forests, tidal marshes and seagrass meadows) are gaining recognition as a natural solution to climate change mitigation and adaptation targets (Macreadie et al., 2021).

Ireland has a vast marine territory of approximately 880,000km2 (Figure 4.2). It is therefore critical to ensure that it is appropriately managed to continue functioning as a carbon sink and does not become a carbon source through mismanagement (Cott et al., 2021). Ireland's two blue carbon sinks are approximately 100km2 of saltmarsh habitat and 62km2 of seagrass habitat in our marine territory, but the actual extent of the latter remains to be determined. The vast majority of the carbon pool is soil organic carbon, as opposed to living biomass, which dominates tropical forests, i.e. coastal vegetation deposits the vast majority of its carbon in the soil rather than forest (Cott et al., 2021).

Cott et al. (2021) outline several pathways for Ireland to integrate blue carbon and marine carbon habitats into UNFCCC policy (e.g. nationally determined contributions or national inventory reporting); however, stress that these mitigation frameworks require stringent methodologies and the existing science is not adequate to allow for their inclusion at present. Other countries have attempted to categorise blue carbon efforts by (Herr et al., 2018):

1. LULUCF – including coastal wetlands as part of LULUCF;
2. conservation, protection and restoration of habitats– including coastal wetland adaptation solutions along with other relevant marine habitats with reference to conservation management and protection;
3. coastal zone management – including information and making specific reference to planning tools, such as the Integrated Coastal Zone Management system;
4. fisheries – provide co-benefits from better ecosystem management and look at more options for job generation along with developing adaptation and resilience measures .

A.5 Is a 100% Renewable Electricity Power System Possible?

Within the literature, there is a consensus on the possibility of a modern electricity system to operate without conventional fossil fuel generation (Breyer et al., 2022). However, the necessary technical solutions in power electronics are not yet commercially available and innovation and large-scale testing would need to accelerate. High shares of variable renewables profoundly change the management of an electricity system. There are two types of electricity generation: synchronous generation and non-synchronous generation (Box A.1).

Box A.1 What is synchronous and non-synchronous generation?

Synchronous generation can produce the same amount of electricity all the time if it instructed to do so. It is reliable and predictable, and therefore easy to bring onto the grid. Fossil fuels such as coal, oil and gas are a type of synchronous generation.

Non-synchronous generation produces a different amount of electricity depending on the resource available. This makes it more difficult to bring onto the grid. Most renewable forms of energy, such as wind and solar, are types of non-synchronous generation. This is because the amount of wind and sun is always changing and therefore cannot be relied on to produce power as and when needed like conventional plants.

Non-synchronous generation, including wind, solar and high-voltage direct current interconnection (i.e. the means by which offshore wind will connect to land), provide none of the inertia currently needed to keep grid frequency stable and resist sudden changes due to faults or transients. Research is still ongoing into if and how the grid can remain stable and reliable in the total absence of inertia that is currently provided by large synchronous generators. Several options can conceptually be used to mitigate this, including:

- Keeping conventional plants on the system; however, in the absence of widespread CCS with very high capture rates, this is not compatible with a net zero future.
- Using synchronous condensers, which, like conventional power plants, can be deployed.
- Using innovative converters in renewable generation assets to provide 'grid-forming' services. Operating a network with only converter-based devices, such as wind and PV, while ensuring power system stability can be technically feasible in principle, but needs further testing and demonstration at a large scale.

The total installed capacity of variable renewable generation in Ireland is set to be as high as 22GW by 2030 (Department of the Environment, Climate and Communications, 2021c). With demand expected to peak at less than 9GW and average between 5.3 and 6.3GW (EirGrid and SONI, 2020), there will clearly be times when supply exceeds demand. 'Dispatch down' refers to times when EirGrid, as the transmission system operator, instructs a renewable electricity generator to produce less electricity or even to shut down entirely. There are several curtailments and constraints (Box A.2). In 2020, the total wind energy dispatch down in Ireland was 11.4%, 5.3% due to curtailment and 6.1% due to system constraints (EirGrid, 2021). This equates to 1,448GWh of unused wind energy, which is equivalent to the annual demand of around 290,000 homes[29].

Box A.2 What is renewable energy curtailment and constraints?

Curtailment refers to the dispatch down of wind/solar for system-wide reasons. There are different types of system security limits that necessitate curtailment:

- system stability requirements (synchronous inertia, dynamic and transient stability);
- operating reserve requirements, including negative reserve;
- voltage control requirements;
- system non-synchronous penetration (SNSP) limit.

Constraint of wind and solar can occur for two main reasons:

1. more wind generation than the localised carrying capacity of the network;
2. during outages for maintenance, upgrade works or faults.

Source: EirGrid and SONI (2021b).

The most common form of curtailment is the SNSP limit. Ireland's electricity system, like most other electricity systems in the world, operates at a frequency of 50Hz. With fossil fuel generators this is very straight forward because they generate electricity at the same frequency. However, wind energy is 'non-synchronous', which means that the frequency at which wind generates electricity is not 'synchronised' with the system at 50Hz. Ensuring that our frequency levels stay steady is probably the single most important priority in managing the electricity system, and so EirGrid have put in place the SNSP limit to ensure that the volume of wind energy is manageable. Since the first quarter of 2022, EirGrid have been trialling a raised limit of 75%, which is part of the preparations to reach a target of 95% by 2030 (EirGrid plc and SONI Ltd, 2021). Limits on SNSP, or in other words the amount of renewable generation the grid can handle, is a binding constraint on the power system in deep decarbonisation scenarios for Ireland. If the Irish electricity grid can increase the stable levels of acceptable variable renewable generation, then this will affect the generation mix and the level of electrification, and will reduce the marginal abatement cost of CO_2 (Glynn et al., 2019).

[29] Based on 5,028kWh per home per year (table 34 in SEAI, 2021c).

Even with the raised SNSP, there will still be times when the sun does not shine and wind does not blow. Within international literature on a 100% renewable electricity system, this issue is addressed with large amounts of hydropower, bioenergy, nuclear power or interconnection (Heard et al., 2017; Hansen et al., 2019; Zappa et al., 2019; Breyer et al., 2022). However, the Irish power system has limited access to these options. This makes the managing of variable renewable sources all the more difficult. In their absence, Mehigan and Deane (2020) found that in the short term (out to 2030) conventional generation plays a necessary role in generation, system services and flexibility. The amount of natural gas generation capacity is much like today's capacity, but it will run for fewer hours and will produce less energy. Looking beyond 2030 towards a net zero system, CCS, means of long-term storage or alternatives in bioenergy and hydrogen will be needed. As detailed in section 4.8, curtailed wind energy could be used to produce hydrogen, which can be used in converted gas generators at times when the wind does not blow. Connolly et al. (2011) proposed a 100% renewable energy system for Ireland, which relied on large amounts of biomass generation. More recently, Yue et al. (2020b), when examining pathways for a 100% renewable energy system (covering heat, transport and electricity) by 2050, found that electricity was dependent on biomass imports unless much larger shares of ocean energy could be deployed.

Despite the significant operating challenges outlined in this section, the power system on the Island of Ireland is one of the most reliable power systems in Europe (Mehigan and Deane, 2020). In 2019, the total system minutes lost due to faults on the main system attributable to SONI (the system operator for Northern Ireland) was 0.92 minutes and to EirGrid was 0.17 minutes. The progress to date integrating onshore wind energy makes Ireland a world leader in brining non-synchronous generation onto the electricity grid. However, continuing this trend will be difficult, requiring new forms of dispatchable generation, upgrades to the transmission system, further development of interconnection, storage and demand flexibility. As Wind Energy Ireland warns, "Our electricity grid is not fit for purpose. It is a grid designed for a fossil fuel economy in the late 20th century" (Baringa and TNEI, 2022, p. 7). Achieving 100% renewable electricity will require significant upgrades to our grid, such as the north–south or Celtic interconnectors (section 4.3.2). Over the last decade, these infrastructure projects have sparked a lot of local opposition and failed to be delivered, highlighting that this constitutes more than just an engineering challenge (section 8.3).

Another important option is demand-side response, management or flexibility. This involves moving energy demand to times when renewable energy supply is high (McKenna et al., 2015). In the case of large energy users, EirGrid identify the need for 'demand-side units', which can be instructed to reduce demand when needed (EirGrid plc and SONI Ltd, 2021). At the household level, real-time data provided by smart metres might allow customers to make more careful choices about when to operate key appliances (Darby, 2020). For example, running a washing machine in middle of the day when the sun is shining or charging an EV overnight when wind is strong, but there is little demand. Given that this is a highly valuable service for the grid (Lynch et al., 2019), particularly during times of peak demand, Curtis et al. (2020) propose that households could be paid for shifting demand in this manner. Rigoni et al. (2021) have also looked at the demand response aggregators, which would bring a group of households together to operate as a single provider. However, the trial of smart metres examined by Belton and Lunn (2020) found that consumers struggle to match their electricity usage to appropriate tariffs and generally prefer simpler options at the cost of better savings. While the move to more distributed forms of generation (i.e. solar PV), home energy controls and smart metering will expand the role of households in the energy market, this does not necessarily mean that it can be assumed that all households actually want a more active role.

Clean generation that is dispatchable would also reduce the amount of storage required by providing an alternative source of electricity during periods of low renewable output. Natural gas power plants have traditionally played this role, but must gradually be replaced by solutions that do not produce GHG emissions (section 4.7). Plants could be retrofitted to operate on biomethane (section 4.5.2) and/or hydrogen (section 4.8), providing the backup required and at a potentially lower cost than batteries alone. However, while hydrogen burned for power generation may not produce CO_2 emissions, it does produce other air emissions, such as nitrogen oxide, which will need to be carefully considered.

Although some level of curtailment will remain even in an optimised system (Steurer et al., 2017), transmission system operators are mandated by the EU to minimise curtailment (European Union, 2009). An option to provide a gaseous fuel source that has been gaining interest is the proposal to convert excess renewable electricity into pressurised hydrogen using electrolysis (see explanation in section 4.8). International literature proposes that this could either supplement or offset the requirement for interconnection and more traditional storage methods (Robinius et al., 2018). However, studies in Ireland have found that solely relying on curtailed wind energy as a source of electricity will not be sufficient to make the investment in necessary 'power-to-gas' infrastructure economically viable (McDonagh et al., 2019a, 2020). It nonetheless emerges as a necessary means to balance the system if bioenergy input is limited (Yue et al., 2020b).

A.6 European Union Climate Policy

The European Green Deal introduced revised targets for Europe to achieve an economy-wide reduction in emissions of at least 55% in 2030, compared with 1990 levels. This was written into law by the European Climate Law, setting the ambition for Europe to become climate neutral by 2050 (European Council, 2022a and the intermediate target of reducing net GHG emissions by at least 55% by 2030 compared with 1990 levels, known as 'Fit for 55' (European Council, 2022b). Under this new ambition, some key elements are:

- A new target to reduce emissions by 61% from EU ETS sectors by 2030, compared with 2005 levels (European Commission, 2022a). This represents an increase of 18 percentage points compared with the –43% target under the existing legislation. To reach this target, the Commission proposes a one-off reduction of the overall emissions cap by 117 million allowances ('re-basing'), and a steeper annual emissions reduction of 4.2% (instead of 2.2% per year under the current system).
- For transport, the proposal sets a new target of 100% reduction for 2035. This means in practice that from 2035 it will no longer be possible to place cars or vans with an internal combustion engine on the market in the EU (European Council, 2022d).
- For renewable energy, it was proposed to increase the EU-level target of at least 32% of renewable energy sources in the overall energy mix to at least 40% by 2030 (European Council, 2022c). In response to the Russian invasion of Ukraine, one of the core pillars under REPowerEU was to increase this target to a 45% share by 2030 (European Commission, 2022d) (see evolution of the target in Figure A.8).

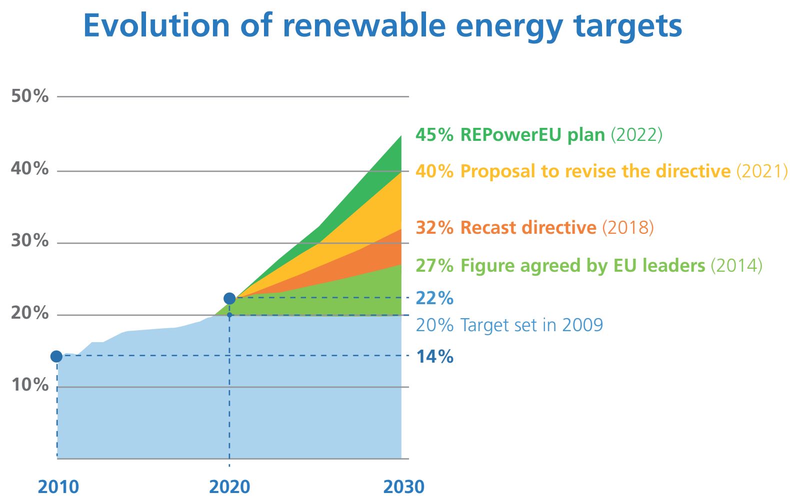


Figure A.8 EU renewable energy target for 2030. Source: European Commission (2022c).

- Treatment of LULUCF emissions: Under the current (40% target) Effort Sharing Regulation, 280Mt of emissions credits are allowable from net emissions removals in the period to 2030. The draft EU Climate Law limits emissions removals to 225MtCO_2.

The European Climate Law also includes the following elements (European Commission, 2021b):

- recognition of the need to enhance the EU's carbon sink through a more ambitious LULUCF regulation;
- as part of the Fit for 55 legislation, the AFOLU sector is expected to reduce emissions by 55% and the minimum target at EU level for 2050 would be net zero emissions from a combined AFOLU sector;
- a process for setting a 2040 climate target, taking into account an indicative GHG budget for 2030–2050 to be published by the Commission;
- a commitment to negative emissions after 2050;

- the establishment of a European Scientific Advisory Board on Climate Change, which will provide independent scientific advice;
- a commitment to engage with sectors to prepare sector-specific roadmaps charting the path to climate neutrality in different areas of the economy;
- stronger provisions on adaptation to climate change.

The EU Methane Strategy, recently published as part of the 'Fit for 55' package, envisages a 35% cut in methane relative to 2005. However, this primarily focuses on reductions in fossil methane, which comprises 20% of EU methane.

A.7 Trends in Greenhouse Gas Emissions by Type

Long-term trends in CO_2 emissions demonstrate the relationship between economic activity and energy/emissions (Figure A.9). CO_2 emissions grew steadily in the 1990s due to the boom in economic activity. There was then a slight drop in the earlier 2000s before a return to growth up until 2008 when the economic crash caused a significant drop. More recently, with economic activity returning, emissions grew between 2014 and 2016, before gradually starting to decrease, which has been mainly thanks to the growth in renewable electricity, as noted in section 2.3.

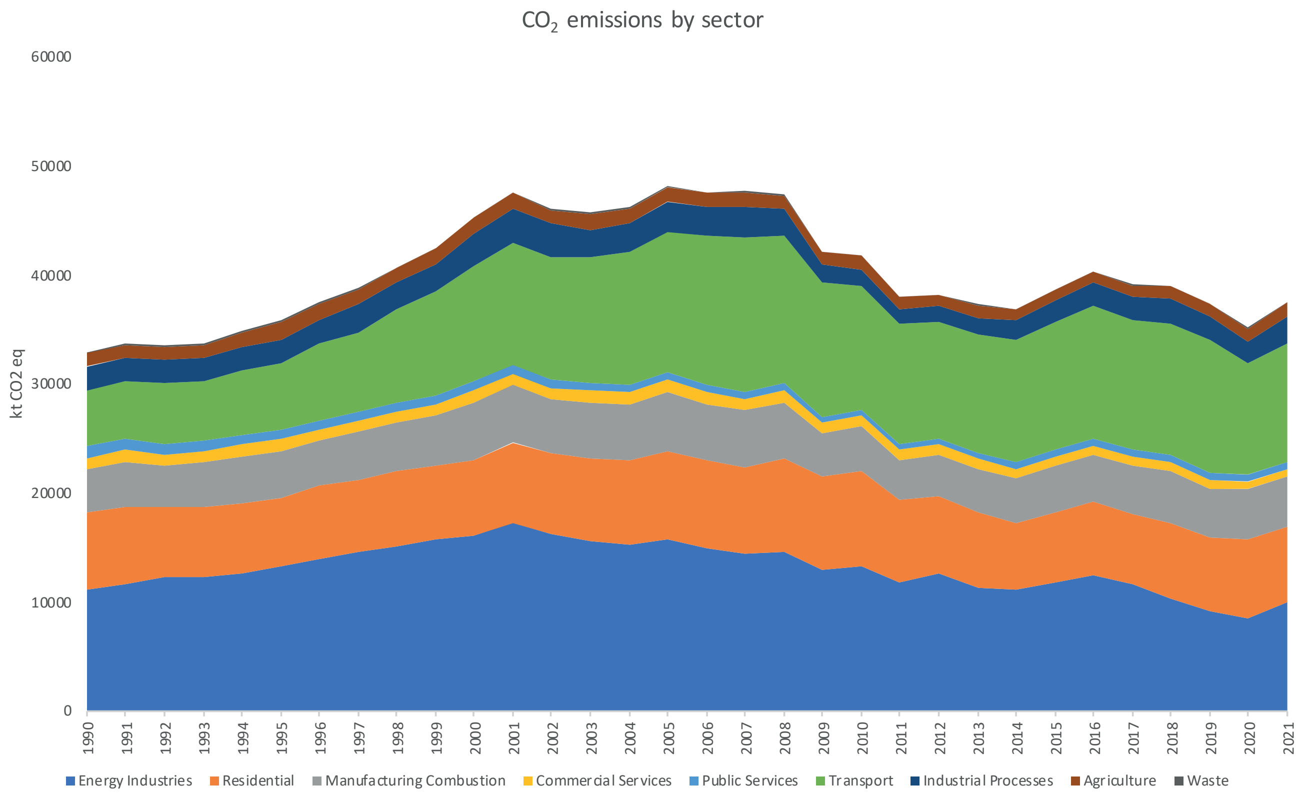


Figure A.9 Ireland's CO_2 emissions by sector from 1990 to 2021. Source: EPA (2022f).

The transport sector through the burning of petrol and diesel is the largest contributor to energy-related CO_2 emissions, followed by the residential sector due to the reliance on oil and gas in home heating (Figure A.9). Energy demand in these key sectors is a result of Ireland's dispersed population and large single family homes (section 5.1). The only sector to make significant progress over the period 2005–2021 was the electricity sector. The widespread deployment of onshore wind and reduction in coal generation halved the emissions intensity of electricity from $636gCO_2kWh^{-1}$ in 2005 to $348kgCO_2kWh^{-1}$ in 2021 (SEAI, 2022c) (Figure A.10).

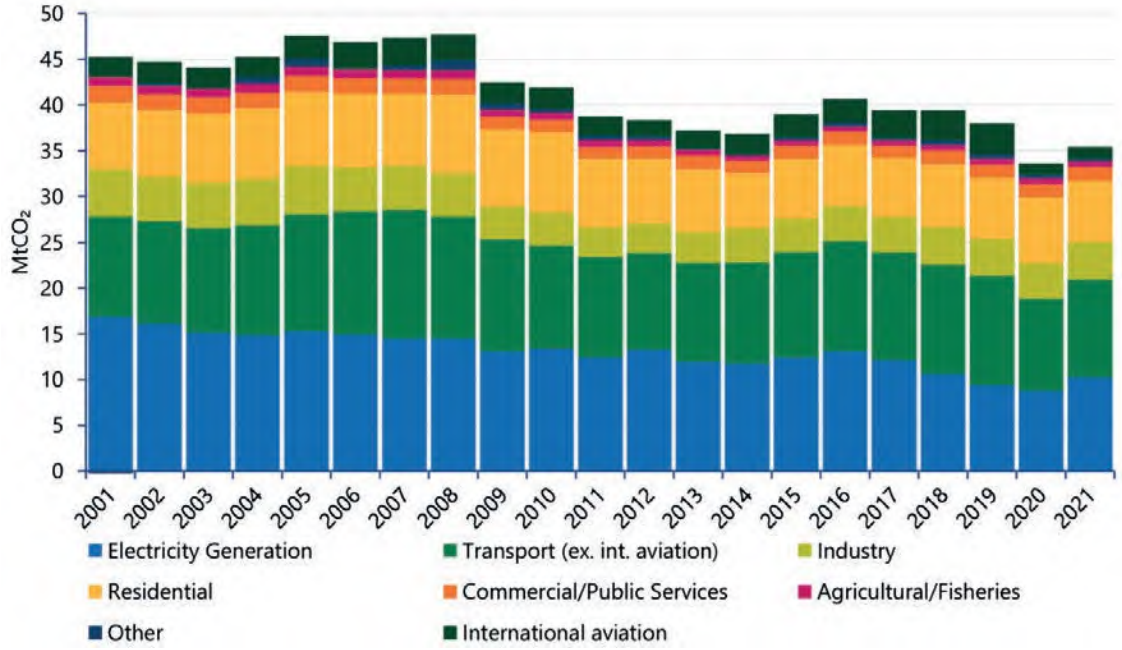


Figure A.10 Energy-related CO_2 emissions by sector 2005–2021. Source: SEAI (2022c).

CH_4 is the second most significant contributor to GHG emissions in Ireland. In 2020, CH_4 from agriculture accounted for just under 12% of total GHG emissions in the EU (European Environment Agency, 2021), compared with 36% in Ireland (EPA, 2022e). This is due to the dominance of livestock rearing in the agriculture sector. The only other developed nation with a similar agriculture sector is New Zealand, where CH_4 accounted for 44% of GHG emissions in 2020 (New Zealand Ministry for the Environment, 2022).

The trends in CH_4 emissions are closely linked to livestock numbers (Figure A.11). In 2021, the agriculture CH_4 emissions were 16.1MtCO$_2$-eq, 19% higher than in 1990 (13.5MtCO$_2$-eq.) (EPA, 2022b). Between 1990 and 1998, CH_4 increased gradually, driven by an increase in livestock numbers. This trend was reversed between 1998 and 2011 because of falling livestock numbers due to reform of the Common Agricultural Policy (CAP). More recent changes to agriculture policy, promoting an intensification of dairy production, has seen a steady increase in emissions. This was primarily a result of the abolition of EU milk quotas. This has left Ireland with a poorly balanced food system. The vast majority (80%) of the food produced here is exported, while the vast majority (95%) of the food eaten here must be imported.

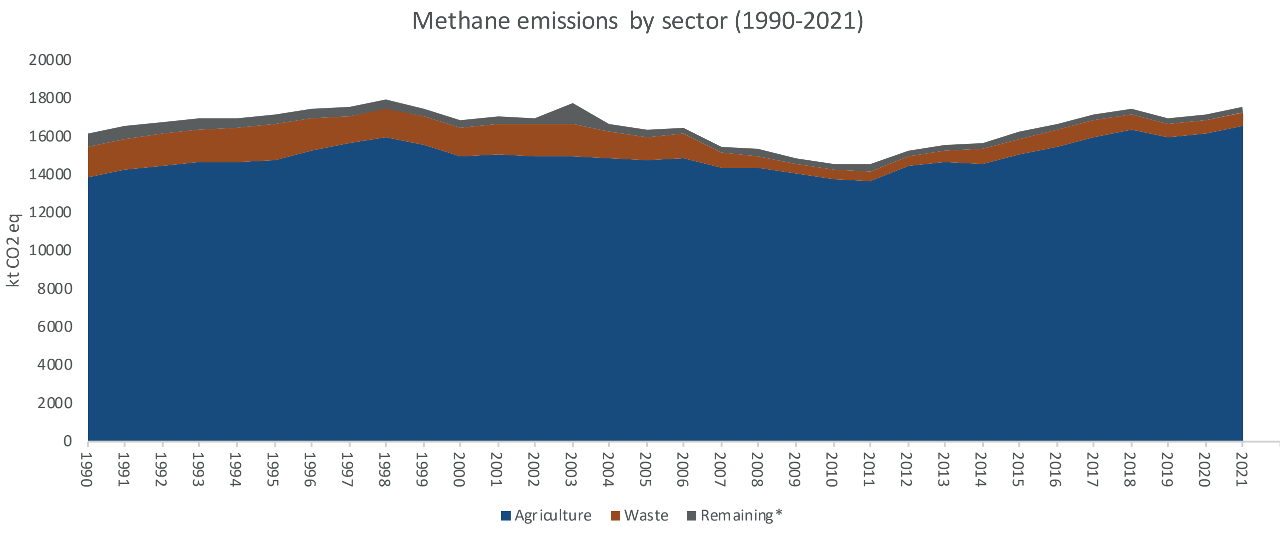


Figure A.11 Ireland's CH_4 emissions by sector from 1990 to 2021. *Very small levels (< 0.5MtCO$_2$-eq) in remaining sectors (residential, energy industries, transport, manufacturing combustion and services). Source: EPA (2022f).

As in the case of CH_4, emissions of N_2O are linked to livestock numbers. They increased between 1990 and 1998 due to increased use of synthetic fertilisers and increased amounts of animal manures associated with rising animal numbers over that period. Emissions of N_2O subsequently show a clear downwards trend following reductions in synthetic fertiliser use and organic nitrogen applications on land, as a result of the effect of the common agriculture policy reform on animal numbers and the closure of Ireland's only nitric acid plant in 2002. Nitrous oxide emissions decreased by 6.7% from their 1990 level of 6.5MtCO_2-eq to 6.1 MtCO_2-eq in 2021 (EPA, 2022b).

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Abbreviations and symbols

4GDH	fourth-generation district heating
ACRES	Agri-Climate Rural Environment Scheme
AFOLU	agriculture, forestry and other land use
AR6	Sixth Assessment Report from the Intergovernmental Panel on Climate Change
BECCS	bioenergy with carbon capture and storage
BER	building energy rating
BEV	battery electric vehicle
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CDR	carbon dioxide removal
CH_4	methane
CNG	compressed natural gas
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CO_2-we	carbon dioxide warming equivalent
COP	Conference of the Parties
CSO	Central Statistics Office
DACCS	direct air carbon capture and storage
DAFM	Department of Agriculture, Food and the Marine
DECC	Department of Environment, Climate and Communications
EBI	Economic Breeding Index
ETS	Emissions Trading System
EU	European Union
EV	electric vehicle
EPA	Environmental Protection Agency (Ireland)
ESRI	Economic and Social Research Institute
FAME	fatty acid methyl esters
GDP	gross domestic product
GHG	greenhouse gas
GOBLIN	General Overview for a Backcasting approach of Livestock Intensification
GVA	gross value added
GWP	global warming potential
H_2	hydrogen
HGV	heavy goods vehicle

HVO	hydrotreated vegetable oil
I3E	Ireland Environment, Energy and Economy
IAM	integrated assessment model
ICE	internal combustion engine
IEA	International Energy Agency
IMO	International Maritime Organization
IMP	illustrative mitigation pathway
INDC	intended nationally determined contribution
IPCC	Intergovernmental Panel on Climate Change
LCOE	levelised cost of electricity or energy
LGV	light goods vehicle
LULUCF	land use, land use change and forestry
MACC	marginal abatement cost curve
N_2O	nitrous oxide
NDC	nationally determined contribution
NET	negative emission technology
OECD	Organisation for Economic Co-operation and Development
PM	particulate matter
PM2.5	particulate matter with a diameter of ≤2.5μm
PV	photovoltaics
RES-E	renewable energy share in electricity
RES-H	renewable energy share in heating and cooling
RES-overall	overall renewable energy share
RES-T	renewable energy share in transport
RESS	renewable electricity support scheme
SDG	Sustainable Development Goal
SEAI	Sustainable Energy Authority of Ireland
SEC	Sustainable Energy Communities
SNSP	system non-synchronous penetration
SOC	soil organic carbon
SR1.5	Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C
SUV	sports utility vehicle
TIMES	The Integrated MARKAL-EFOM System
TRL	technology readiness level

UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
VRT	Vehicle Registration Tax
WAM	with additional measures
WEM	with existing measures
WGIII	Working Group 3 in the Intergovernmental Panel on Climate Change

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epa
Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

seai
SUSTAINABLE ENERGY AUTHORITY OF IRELAND

An Roinn Iompair
Department of Transport

sfi
science foundation ireland

ICCA
IRELAND'S CLIMATE CHANGE ASSESSMENT