National Heat Study

Net Zero by 2050

Key Insights, Evidence and Actions

SUSTAINABLE ENERGY AUTHORITY OF IRELAND

NET ZERO BY 2050

KEY INSIGHTS, EVIDENCE AND ACTIONS

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The National Comprehensive Assessment for Ireland was commissioned by a project team across the SEAI Research and Policy Insights Directorate and developed with the assistance of Element Energy and Ricardo Energy and Environment.

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ACKNOWLEDGEMENT

SEAI would like to convey our thanks to all involved in the development of the National Heat Study. Your support and contributions were an essential part of the process, and we hope to continue to collaborate in the months and years ahead.

SUSTAINABLE ENERGY AUTHORITY OF IRELAND

SEAI is Ireland's national energy authority investing in, and delivering, appropriate, effective and sustainable solutions to help Ireland's transition to a clean energy future. We work with the public, businesses, communities and the Government to achieve this, through expertise, funding, educational programmes, policy advice, research and the development of new technologies.

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Reducing greenhouse gas emissions from the energy we use for heating and cooling is a difficult challenge. Over the last decade, many businesses and households have added insulation, installed more efficient technology and used less solid fuel. However, annual emissions from energy used for heating have been on an increasing trend since 2014, when Ireland emerged from the effects of the global 2008 recession. This trend must be reversed immediately if the heat sector is to meet its share of the required emissions reductions.

[1] www.gov.ie/en/publication/e4332-introductory-text-for-publication-of-the-national-comprehensive-assessment-on-govie/

Key Insights

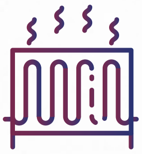
Heat related CO_2 emissions are rising.

Heat related CO_2 emissions are 14.1MtCO_2. These come from the fossil fuel combustion in homes, businesses and industry, and indirectly from the use of electricity. Together they account for 38% of total energy-realted CO_2 emissions or 24% of total national GHG emissions. Despite many homes and businesses taking up government grants over the last decade, the emissions from heating are up 12% from the post-recession lows of 2014.

Ireland aims to reduce emissions by 51% from 2018 levels by 2030.

The current Climate Action Plan measures are unlikely to deliver enough heat-related CO_2 cuts to meet a proportional share.

Current policy measures are unlikely to deliver the Climate Action Plan goals. The modelling shows an unprecedented level of additional policy effort, that goes beyond current heat related Climate Action Plan goals, is required to ensure heat related emissions stay within the proposed carbon budget limits. The findings provide direction as to the prioritisation of effort and the need for extended measures to decarbonise heat as quickly as possible.



District heating is a technology that offers additional potential. It is proven and available now. The analysis suggests it could provide as much as around 50% of building heating demand in Ireland.

The analysis shows that heat supplied to buildings through district heating networks is a competitive option that can be widely deployed. The potential identified is more than that considered in recent policy planning and offers the chance for additional emissions cuts. Heat networks are a mature infrastructure that a variety of heat energy sources can supply. The Climate Action Plan measures that seek to address the market and regulatory gaps that exist in Ireland can address the regulatory, planning and financial barriers to deployment.

Evolving existing policy supports to focus on replacing fossil fuels in buildings can have a more significant and immediate emissions reduction impact than a fabric-first approach.

The current support scheme incentives are designed based on the 'fabric-first' principle, which asks consumers to use the available fabric technologies and financial budgets to reduce heat demand before installing a renewable heating system. However, this approach is not guaranteed to be consistent with the rapid decarbonisation needed to meet the goals of the Climate Action Legislation. It is also not financially viable for a large proportion of consumers in the analysis. Support scheme design that focuses on meeting the minimum levels of fabric performance to support a switch away from fossil fuel heating sources is likely to see more uptake and require less investment. Additional fabric improvements can happen if higher fuel costs or lower technology costs provide more attractive paybacks.

Available domestic solid and gaseous biomass fuels are used in all scenarios. Nationally appropriate sustainability governance is required to minimise upstream emissions, align with circular and bioeconomy goals, and avoid increasing emissions in non-energy sectors.

Between 7%-17% of heat demand is supplied by bioenergy by 2030 and a similar proportion in 2050. Sites that are sized below the mandatory EU threshold for sustainability governance use most of this energy. The resource assessments for the biomass feedstocks considered upstream greenhouse gas emissions and other important sustainability aspects, such as biodiversity. Hence, the resource estimates are based on specific good practice approaches to their cultivation, harvesting, collection and use. Energy crops grown in ways that depart from these assumptions risk causing environmental damage leading to more greenhouse gas emissions in the land use and agricultural sectors. Nationally appropriate sustainability governance measures and other market development supports can help biomass supply chains contribute to their full potential and reduce the risk of emissions increases in other sectors.

[1] In line with government policy green hydrogen produced from renewable sources was the only hydrogen production route considered in the analysis

Heat pumps are a prominent technology in all scenarios and in all sectors. Rapid emissions cuts require deploying the technology at scale.

Heat pumps are widely used to decarbonise space and water heating in buildings and low-temperature heat at industrial sites. Capital costs are a barrier in the residential sector, and additional policy support is needed to drive uptake. The economics are more favourable in other sectors. Awareness-raising, marketing campaigns and supply chain support can aid the uptake of heat pump technologies in the services and industry sectors.

The availability of sustainable biomethane is linked to land-use choices and requires increased productivity in the agricultural sector. It can be a competitive option if the costs and benefits are shared across all gas grid users or used off-grid to displace oil.

The biomethane resource is estimated based on a detailed spatial analysis of the potential for red-clover grass silage and cattle slurry, and national estimates of food and other waste streams. The resource is an estimated 4-8% of current gas fuel use. It is lower than previous estimates for two reasons: grass silage feedstock is limited to environmentally suitable and accessible land, and farmer uptake is considered. If a reduction in the size of the national herd were to occur, the resource estimate could increase to 11%. Biomethane from waste is the lowest cost. Biomethane generated from sustainable slurry and grass silage mixes at the estimated volumes can also be competitive if the costs and benefits are shared across all gas customers or if it is transported directly to off-grid sites using more expensive and higher-carbon oil fuels.

Net-zero emission pathways with the lowest cumulative emissions use more electric heating technologies. Scenarios focused on a hydrogen gas grid have more cumulative emissions.

Green hydrogen is a potential large-scale solution for gas-based industry and power generation[1]. The potential hydrogen resource is much greater than Ireland's heat demand. However, it is unlikely to be commercially available at scale until the 2030s, whereas electrification technologies are available now. This means that hydrogen plays a smaller role in rapid decarbonisation scenarios than electrification. The Climate Action Plan contains measures to build the regulatory infrastructure required to deploy hydrogen. Further effort to accelerate the commercial availability of competitively priced green hydrogen can enhance its role in the heat sector and allow the fuel to contribute to reducing emissions sooner.

Decarbonising the electricity grid is essential to cutting heat-related emissions.

The analysis shows that electricity use for heating has a prominent and increasing role in all the scenarios examined. Delivery of renewable capacity and supporting grid flexibility must stay ahead of demand growth to realise the benefits of emissions savings from this demand-side electrification of heat. The high-resolution electricity modelling shows power sector emissions reducing by about 50% by 2030 (relative to 2018), while demand increases by 61-69% in the same period – driven by data centre demand growth, heat electrification, and electric vehicles. The power sector modelling sees a total of 10-11 GW of wind capacity installed by 2030 to meet a renewable electricity percentage of at least 70% in all scenarios. The Climate Action Plan is targeting an 80% renewable electricity share by 2030, and the delivery of this will further enhance the heat sector savings shown here.

A timetable for fossil fuel phase-out in all sectors is needed as soon as possible to meet net zero by 2050.

The results indicate some consumers are likely to choose fossil fuel technologies, even with high carbon and fossil fuel prices. This suggests that additional policy is needed to ensure full phase-out. The following fossil fuel phase-out dates have been estimated based on technology lifetimes and other assumptions.

- No new fossil fuel appliances can be installed in buildings post-2035 if net-zero heating emission is to be reached by 2050.
- For industry, given longer technology lifetimes, this timeframe would either need to be sooner (circa 2025), or else unabated fossil fuel technologies will need to be retired before the end of their useful life. This analysis assumes the latter.

The future role of carbon capture, utilisation and storage (CCUS) and negative emission technologies (NETs) as part of economy-wide carbon neutrality is important to define.

The analysis identified several heat and power generation sites that are likely to be suitable for CCUS abatement. Should these sites switch to hydrogen or electricity, they would no longer need CCUS, and the potential for negative emissions would be reduced. However, cement and some other industries are likely to have limited abatement options for their process emissions. Should Ireland wish to have the option to deploy this technology over the long-term role, then advanced planning around the role of CCUS and NETs such as bioenergy carbon capture and storage (BECCS) is needed. Decisions are required on where and how the clustering of sites and infrastructure might be achieved. The role of biomass fuels, where they come from, and in what quantities are also important factors to consider.

Key Evidence

Ireland's Climate Action legislation has set legal requirements for greenhouse gas emissions reductions. By 2030, emissions must be 51% less than they were in 2018, and by 2050, the Irish economy must be carbon neutral[1]. The carbon budgeting process described by the legislation will set out the annual emissions reduction trajectory and set greenhouse gas limits for each sector of the Irish economy to meet these targets. These limits represent Ireland's contribution to the principal aim of the Paris agreement – to curb global temperature increases by restricting the total amount of greenhouse gas emissions emitted into the atmosphere.

Reducing and removing heat energy emissions is a difficult challenge. Over the last decade, many businesses and households have added insulation, installed more efficient technology and used less solid fuel. However, annual emissions from energy used for heating have been on an increasing trend since 2014, when Ireland emerged from the effects of the global 2008 recession. Annual CO_2 emissions from energy used for heat (excluding electricity generation) were 12% higher in 2020 than in 2014; emissions from the residential sector were up 18%, services were up 13% and industry increased by 9%.

The Irish Government has published a Climate Action Plan that identifies actions to turn these trends around. The plan, revised annually, specifies actions that aim to keep emissions within the carbon budget limits for each sector. The first plan required under the Climate Legislation was published in late 2021[2]. Several of the measures identified in the plan rely on the outcome of the work of this National Heat Study to inform the policy ambition.

The National Heat Study aims to provide a rigorous and comprehensive analysis of the options to reduce CO_2 emissions associated with heating in Ireland. The Sustainable Energy Authority of Ireland (SEAI) commissioned Element Energy and Ricardo Energy and Environment to work with SEAI on the study. The project was carried out in close collaboration with the Department of the Environment, Climate and Communications. As well as contributing to national policy, the findings also supported Ireland's second submission to the EU of a National Comprehensive Assessment of the Potential for Efficient Heating and Cooling, as required by Article 14 of the Energy Efficiency Directive. The data, assumptions and outcomes of the National Heat Study are detailed in eight technical reports *(Figure 1)*. The project leaves SEAI with an enhanced modelling and analysis capability to continue providing insights and tackling further work. It has enabled a comprehensive stakeholder engagement that has delivered insights and information and started many new and important discussions. It also provides a detailed set of data and information to inform broader research efforts in Ireland.

Using the National Energy Modelling Framework (NEMF), developed by SEAI, the analysis models four separate pathways to get to net zero emissions from heat energy use by 2050 and compares these to a *Baseline* scenario. Each scenario represents a different energy system context and approach to *decarbonisation*. *Figure 2* contains the high-level detail of the scenarios examined.

This summary report sets out the key insights from the scenario modelling developed via the NEMF. It details the challenges policymakers face across sectors and technologies and outlines the actions and decisions they can take now to deliver on the Climate Action legislation ambition. The report also identifies some areas that require immediate further investigation now and it highlights areas where there are interdependencies across policy goals.

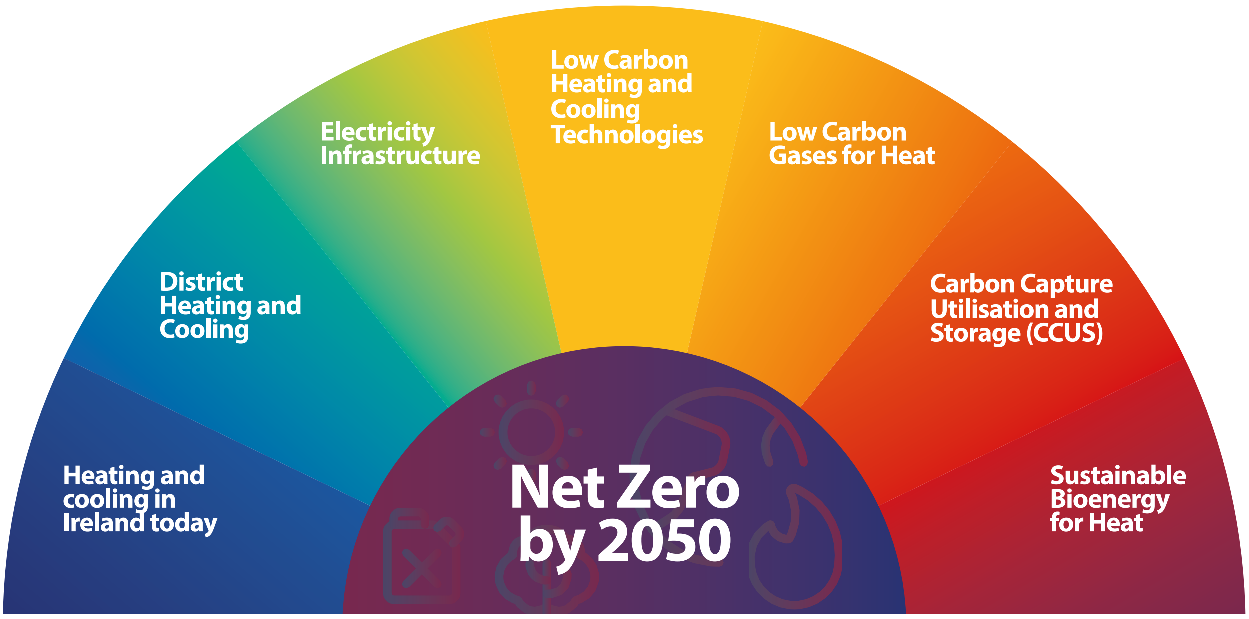


Figure 1: Technical reports from the seven workstreams of the National Heat Study

[1] www.gov.ie/en/publication/e4332-introductory-text-for-publication-of-the-national-comprehensive-assessment-on-govie/
[2] www.seai.ie/data-and-insights/national-heat-study/

The National Energy Modelling Framework (NEMF)

The analysis uses SEAI's NEMF, which has been updated with the data and information from the technical reports. A vital feature of the modelling framework is its focus on the end consumer and their circumstances. This approach allows insight into the challenges faced by consumers considering decarbonisation actions and where policy can help.

The NEMF is a tool that examines aspects such as the variation in technology readiness, technical suitability, cost data and performance data, to assess various scenarios (including potential decarbonisation paths) in Ireland. The archetype model developed for the NEMF contains data on over 680 individual heat demand archetypes, representing a combination of physical and consumer attributes, which in turn provide a detailed description of demand in the residential, services and industry sectors. The physical circumstances of each individual archetype determine what technologies are suitable, their installation costs and what heat demand the technologies need to meet. The model captures the variation in technology readiness and, in each archetype, technical suitability, cost and performance. The cost of the fuel options used by the technologies is modelled in detail. The end consumer's energy bill includes the cost of fuel, the cost of infrastructure and carbon, and other taxes. Bioenergy, electricity and hydrogen supply chains are represented in detail. The costs of gas, district heat and electricity infrastructure are also included. The electricity system is modelled at high resolution and accounts for the investments required to decarbonise and maintain a secure system.

The model uses this techno-economic data to generate payback and lifetime cost estimates for the various technology options available, accounting for policy incentives, taxes and regulations. This payback and lifetime cost information is used with other data on consumer decision-making behaviour to help understand how much uptake may result in various scenarios and in response to policy measures. This simulation approach is used in this analysis to examine what impact a given set of policy measures can have on the energy system. Where technology deployment requires centralised decisions, these are accounted for outside of the consumer decision-making framework. Industrial carbon capture, utilisation and storage (CCUS) and district heating have been dealt with in this way.

1.2 Relationship to Overall Modelling

Scenario	Details
Baseline	Business-as-usual scenario where all sectors continue to use carbon-intensive practices.
	Limited deployment of heat networks, new technologies or fuel switching.
	Includes policy measures from the 2019 Climate Action Plan that had existing implementing measures such as funding and planning or legislation in place by the end of 2020.
	It does not achieve net zero by 2050.
High Electrification	Weighted towards electrification, coupled with minimal amounts of bio-derived gases, CCUS and green hydrogen.
	High levels of heat networks deployment and significant efficiency uptake.
	Achieves net zero by 2050.
Decarbonised Gas	Weighted towards green hydrogen use, CCUS infrastructure or bio-derived gases, or both, coupled with domestic and commercial fuel switching to green hydrogen or bio-derived gases, or both.
	Low levels of heat networks deployment and efficiency uptake.
	Achieves net zero by 2050.
Balanced	Progresses steadily and comprises a mix of cost-effective deployment of low-carbon technologies (electricity, bio-derived gases, green hydrogen).
	Medium level of industrial CCUS, heat networks and efficiency deployed.
	Achieves net zero by 2050.
Rapid Progress	Accelerated progress, driven by policy targets; all low-temperature applications are quickly electrified, while bio-derived gases are prioritised for industry sites.
	High levels of heat networks deployment and energy efficiency uptake.
	Achieves net zero by 2050.

Figure 2: High-level details of the Baseline and Scenarios examined

CO_2 Trajectories and Proposed Carbon Budgets

All the scenarios analysed, except for the *Baseline*, meet net zero by 2050, but some do so with less cumulative emissions than others. *Figure 3* shows the annual, and *Figure 4* the cumulative, CO_2 emissions trajectory for each scenario. The CO_2 emissions come from all fuels used to generate heat energy, including electricity. The scenarios that rely on technologies that are commercially available now perform best – these scenarios reduce CO_2 emissions sooner. The scenarios that wait for promising technologies to mature have more CO_2 emissions in the near term and thus have higher cumulative emissions over the period to 2050.

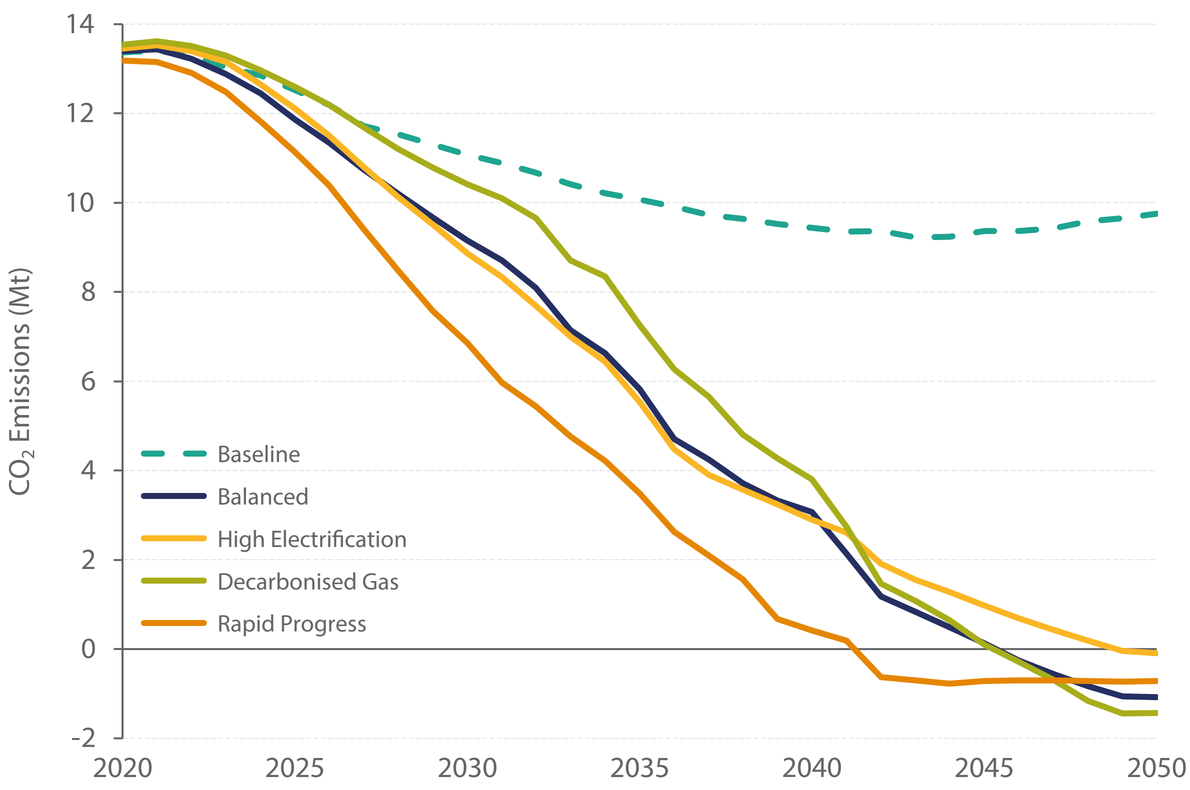


Figure 3: Annual heat-related CO_2 emissions by scenario 2020-2050 ($MtCO_2$)

The *Balanced*, *High Electrification* and *Rapid Progress* scenarios reduce emissions quicker. The availability of low-carbon technologies for heat that are powered by low-carbon electricity in these scenarios is a primary driver of this outcome. The large-scale deployment of heat networks (district heating) and the use of bioenergy also make significant contributions to the CO_2 reduction trends. The *Decarbonised Gas* scenario relies more heavily on green hydrogen and biomethane to achieve net zero. Green hydrogen is unlikely to be available at scale to consumers until the 2030s, and the biomethane resource is not large enough to drive emissions reductions sooner.[1] The *Decarbonised Gas* scenario takes longer to make deep cuts in emissions than the other scenarios. Emissions savings from CCUS technology, including bioenergy CCUS, deployed from the mid-2030s cannot offset this. These factors mean the *Decarbonised Gas* scenario achieves net zero by reducing emissions later than the other scenarios. This delay causes the scenario to have the highest cumulative emissions overall.

The challenge of the 2030 emissions reduction target

As *Figure 3* and *Figure 4* show, an early effort reduces total cumulative emissions. The recent carbon budget proposals put forward by the Climate Change Advisory Council set economy-wide budgets across two periods to 2030[3]. From 2021 to 2025, the budget limit proposes capping total carbon emissions at 295 $MtCO_{2eq}$, representing an average annual reduction of 4.8%. From 2026 to 2030, the proposed budget is set at 200 $MtCO_{2eq}$. equivalent to an 8.3% annual emissions reduction.

The National Heat Study scenarios present insights into the challenges ahead and the efforts required to stay within carbon budget limits. While the budget limits are not applied to energy end uses, heat energy use contributes to emissions in several economic sectors where emissions ceilings will apply, such as built environment, enterprise and public sector. Comparing the emissions trajectories from the scenarios to the carbon budget limits provides insights into the challenge ahead for those sectors that generate a large proportion of their emissions through the use of heat energy.

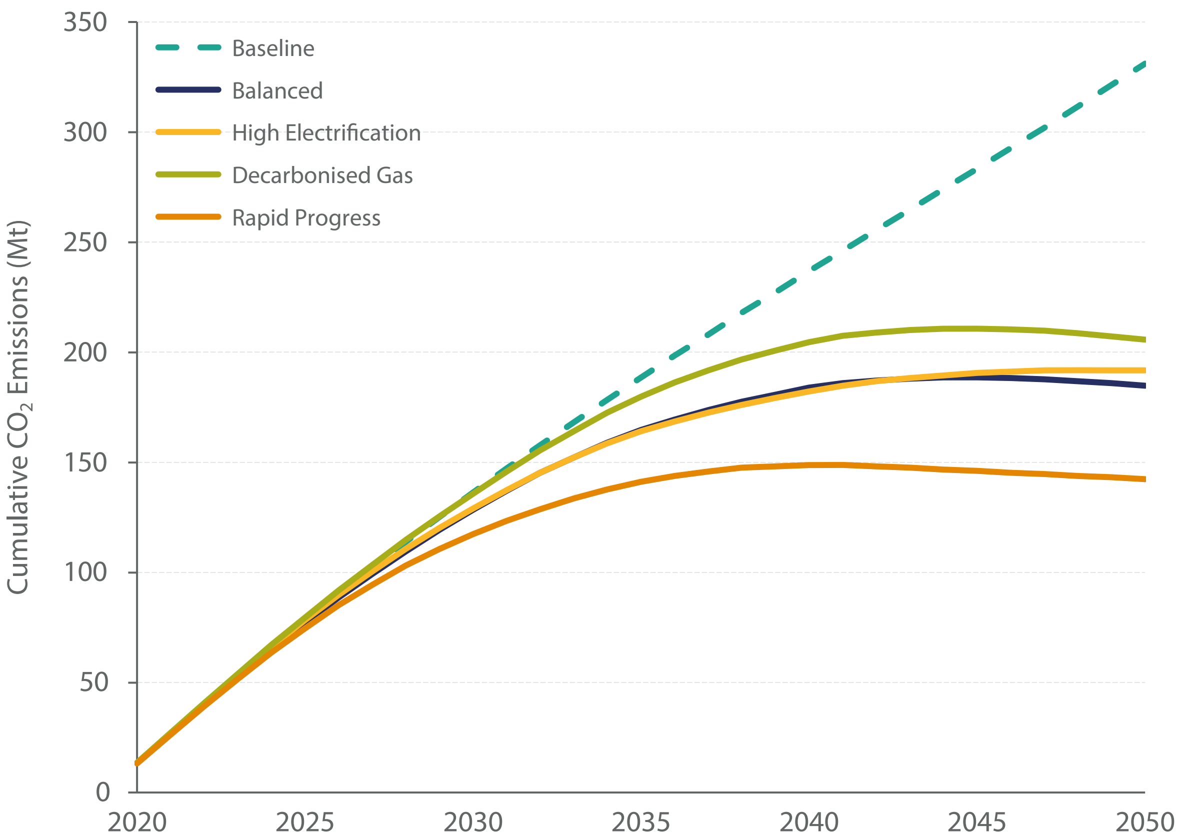


Figure 4: Cumulative heat-related CO_2 emissions by scenario 2020-2050 ($MtCO_2$)

[1] www.gov.ie/en/publication/e4332-introductory-text-for-publication-of-the-national-comprehensive-assessment-on-govie/

Figure 5 shows how the scenarios examined in the National Heat Study compare to the carbon budget proposals. The emissions shown include all CO_2 directly released from the combustion of fossil fuels, the indirect CO_2 emissions related to electricity use as a source for heat and the upstream emissions from the use of bioenergy. All scenarios fall short of emissions limits in the first budget period. Only the *Rapid Progress* scenario meets the reduction threshold in the second. No scenario stays under the implied overall emissions limit from 2021 to 2030.

The *Baseline scenario* falls short of the Climate Action Plan sub-targets because the policy measures[4] do not achieve sufficient low-carbon technology and fuel uptake. Additional policy effort is added in the *Balanced*, *High Electrification* and *Decarbonised Gas* scenarios to achieve the Climate Action Plan activity level targets. For targets such as retrofitting 500,000 homes to a building energy rating of at least B2 and the installation of 600,000 heat pumps, significant additional incentives are required. Meeting these, however, does not ensure a sufficient reduction in CO_2 emissions to meet cuts targeted in the Climate Action legislation.

An unprecedented additional effort is required to stay within the proposed budget limits and to cause sufficient technology and fuel switching away from fossil fuels in combination with rapid decarbonisation of the electricity grid.

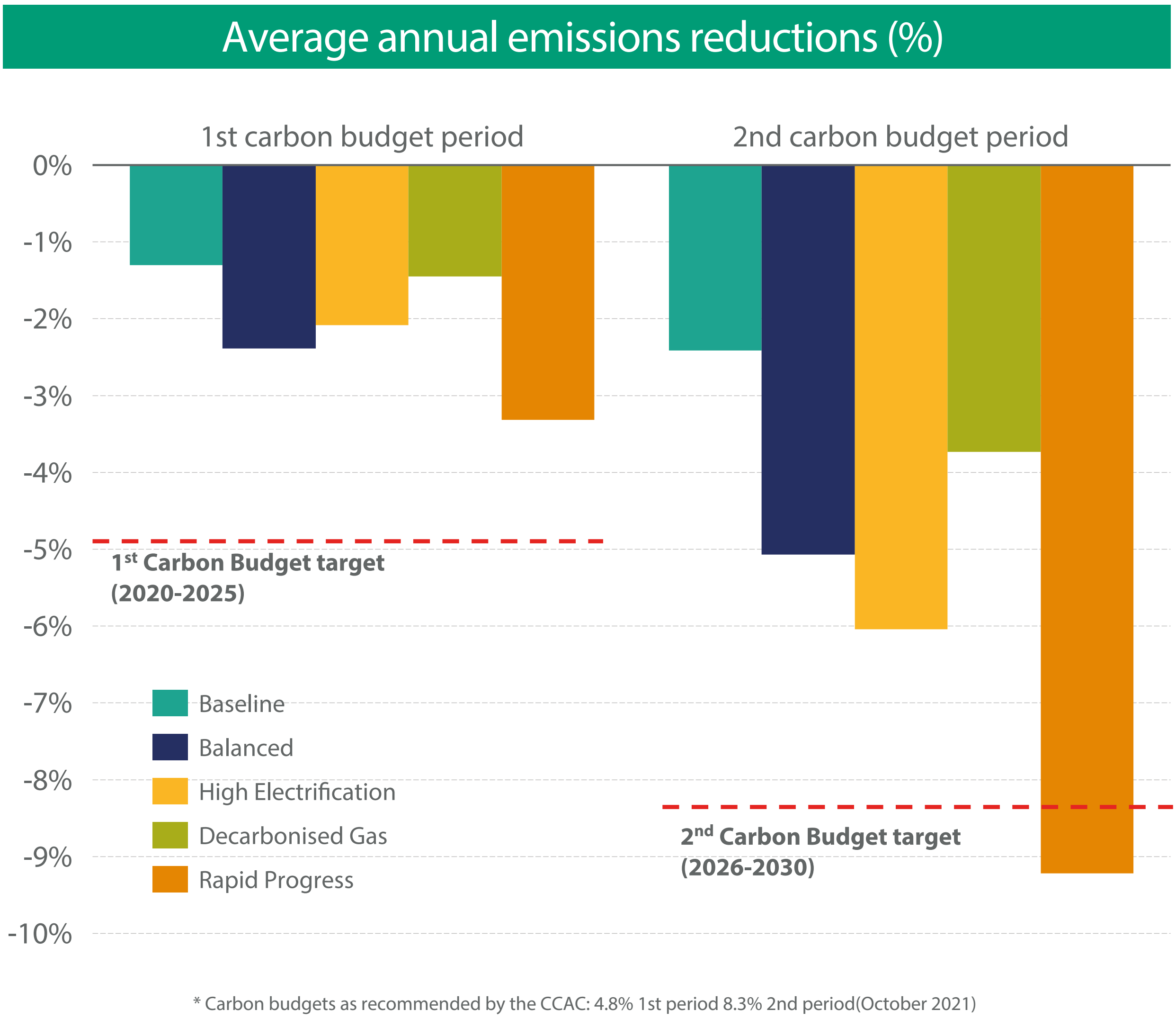


Figure 5: Average annual emissions reductions achieved in each scenario for both carbon budget periods

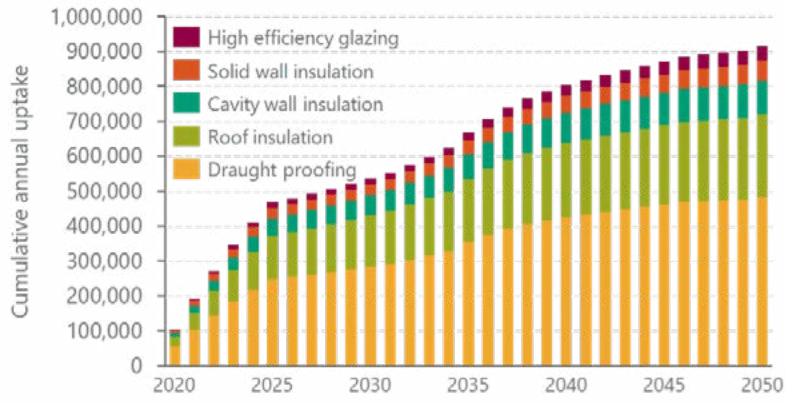
[4] In the Baseline current policy measures are those from the Climate Action Plan 2019 that had existing implementing measures such as funding and planning or legislation in place by the end of 2020.

Heating Demand and Energy Efficiency

Heat demand determines the amount of energy that heat generation technologies must provide. It is a key driver of amounts of fuel usage and CO_2 emissions. Heat demand rises in each scenario and the deployment of energy-efficiency measures in all sectors is not enough to offset the impact of economic and population growth. Additional demand comes from the estimated new builds needed to house an expanding population in the residential sector, which increase from approximately 22,000 new homes per year in 2021 to around 40,000 in 2030 and 56,000 in 2050. New buildings also drive demand growth in the services sector. In the industry sector, heat demand grows in line with the projections for increased economic activity.

The deployment of energy-efficiency technologies in the net-zero decarbonisation scenarios reduces demand relative to the *Baseline*. The residential sector sees the most considerable difference by deploying fabric measures that reduce the heat lost from dwellings. But even in this sector, anticipated savings are modest. Heat demand is 3% more in the *Baseline* scenario than in the net-zero scenarios by 2030 and 5% more by 2050.

Figure 6 shows the uptake of fabric measures in the residential sector and the energy savings these deliver. The charts show the *Balanced* scenario, which offers consumers financial incentives of up to 80% of the capital cost to install fabric upgrades to 2031. From 2032, consumers no longer receive financial incentives but still choose the most cost-effective combination of fabric upgrades and low-carbon heating to decarbonise for their circumstances. Consumers install fabric measures alongside a low-carbon heat source when it results in the lowest overall combined payback.



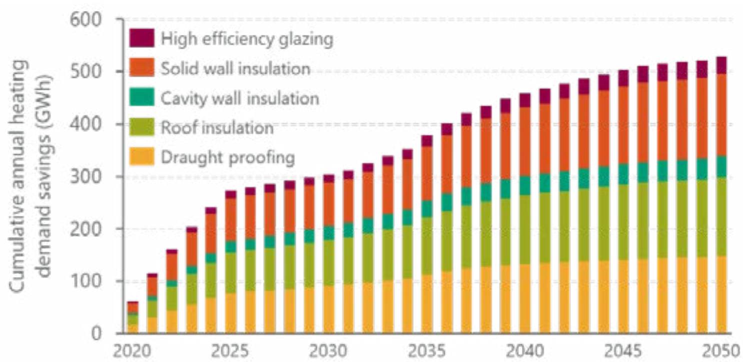


Figure 6: Top: Fabric measures installed in the residential sector; Bottom: Associated heat demand savings by fabric measure (Balanced scenario)

Once a household installs a low-carbon heat supply option, fabric measures do not deliver additional end-use CO_2 emissions reductions. However, in many cases, it makes sense for a household to improve the building fabric to reduce their fuel bills, improve their comfort levels or improve the suitability of their building for low-temperature heating technologies such as heat pumps. The modelling shows that 83% of the residential building stock install some form of heat demand reduction measure in the *Balanced* scenario. As *Figure 6* illustrates, consumers are likely to favour the low-cost and low-hassle fabric measures such as draught-proofing, roof insulation and cavity wall insulation, with other measures seeing limited uptake.

There are several underlying reasons for this.

- Other measures such as solid wall insulation, floor insulation and high-efficiency glazing can bring significant energy savings, but are also the most expensive, have the longest payback periods (see *Figure 7*) and have the most consumer hassle associated with their installation. These factors limit uptake among consumers.
- The NEMF calculates the energy saving and the cost of installing each measure in each building archetype. It also includes estimates of how much potential exists in the building stock for each fabric upgrade type. This data allows a calculation of payback periods and total energy reduction potentials for each measure in each building archetype. *Figure 7* shows the average payback periods for all detached dwellings heated by oil in 2030. The most expensive measures have significantly longer payback periods and are prohibitively long for many building archetypes.
- The potential theoretical savings for energy-efficient measures are unlikely to be seen due to the rebound effect. Most people have a limited budget for heating. Occupants of dwellings with poor thermal performance tend to underheat their dwellings to limit their fuel costs. Upon improving the thermal performance of a dwelling, the occupants can benefit from either reduced energy use and fuel costs, or higher indoor temperatures, or a combination of both. Though increased internal temperatures bring significant health and wellbeing benefits, a significant portion of the theoretical energy and CO_2 savings are often not realised. This is the rebound effect, and we account for it in the modelling presented here.
- In the NEMF, the payback calculations for each fabric measure include the value of the comfort to the consumer. The energy used in an upgraded dwelling to increase the internal temperature, rather than being taken as a reduction in energy demand with the associated fuel bill savings, is included as a notional economic benefit seen by the occupants. This approach captures the value of comfort and wellbeing seen by the bill payer. However, the actual realised energy savings in *Figure 6* (and associated CO_2 emissions savings) are adjusted down to account for the comfort taking rebound.
- In most circumstances, the payback periods for fabric measures become longer when more efficient, lower running cost heat sources are installed. For example, the running costs of a well-installed heat pump are lower than for an oil boiler in most circumstances. Therefore, after a dwelling has a heat pump installed, the payback period for adding additional demand reduction measures increases, all else being equal. Should fuel prices rise in the future for the low-carbon heating options, then the deep fabric upgrades are likely to become more financially attractive to building occupants.

The findings of the National Heat Study suggest a need to evolve the energy efficiency and fabric-first principles for decarbonisation. More rapid decarbonisation of buildings requires policy measures that maximise the number of building owners that choose to replace fossil fuels for heating. Given the limited budgets available to householders and the government, energy-efficiency technologies should be seen primarily as enablers for deploying low-carbon heating supply technologies. This approach will lead to an evolution of policies and measures for more rapid decarbonisation compared to the current approach. However, improvements in building thermal performance remains an important policy goal for health, wellbeing, alleviation of fuel poverty and comfort. These may be better achieved with policies associated with building regulations and planning permission (triggered by building works) rather than with decarbonisation (triggered by replacing heating systems).

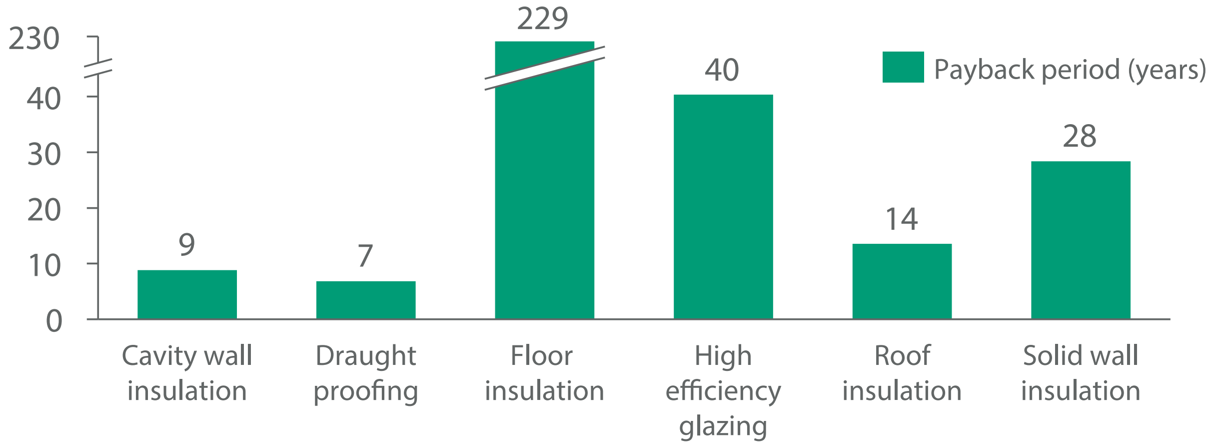


Figure 7: Average consumer payback for fabric measure option in detached, oil-heated dwellings in 2030

Technology and Fuel Use to 2050

Phase-out of unabated fossil fuel use is required to meet net-zero by 2050

All scenarios implement the phase-out of fossil fuel to meet net zero by 2050. The modelling shows that the projected fuel and carbon price increases do not provide a large enough incentive for all consumers to switch to low-carbon heat sources in the net-zero scenarios. Many consumers continue to fuel their energy demand with fossil fuels, and the heat sector continues to emit significant amounts of CO_2.

To achieve net zero by 2050, heat consumers must only choose renewable and low-carbon options (such as electricity, bioenergy or green hydrogen-based heating sources) after a certain point to ensure full turnover to renewable technologies. As part of the scenario design, we considered the latest phase-out year for the scenarios to reach net zero by 2050. We also examined the impact of phasing out fossil fuels sooner.

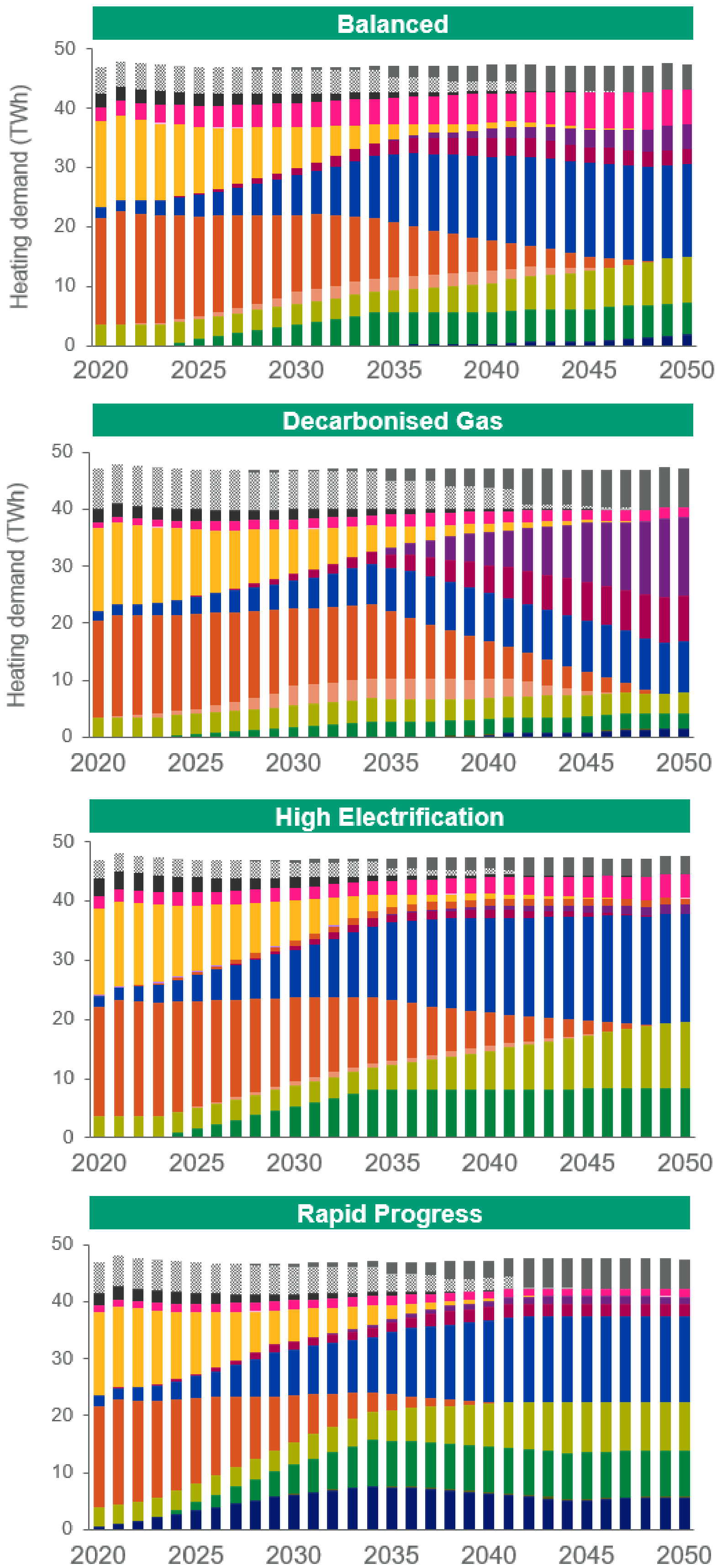
Table 1: Fossil fuel phase-out assumptions for each sector in each scenario

Sector	Baseline	Balanced, High Electrification, Decarbonised Gas	Rapid Progress
Public	No phase-out timeline	2031	2026
Residential		2032	2027
Commercial		2034	2029
Industry		2035	2030
Agriculture		2035	2030

Technology lifetime is the overriding factor in selecting the phase-out year. Fossil fuel technologies used for space and water heating have lifetimes of around 15 years. As such, all consumers deciding how to heat their buildings from 2035 must choose a renewable or low-carbon option for an endpoint of zero to be achieved by 2050.

In the industry sector, technology lifetimes are about 25 years. To reach net zero by 2050, while getting the most out of their heating technologies, industry sector energy managers would need to begin to replace all end-of-life fossil fuel fired heating systems and processes with low-carbon alternatives as early as 2025. However, the feedback from the industry stakeholders during this project suggests that it is doubtful that phase-out can happen this quickly in a sector where energy costs are critical for international competitiveness. A more plausible scenario is that the industry would wait until at least the 2030s before beginning to phase out fossil fuels. However, many industry sites will need to replace their current set of ageing heating technologies between now and then. For the industry sector to meet net zero by 2050 in this scenario, the sites that install new fossil fuel technologies up to the 2030s will have to retire these before they come to the end of their lifetime. This tension is a key aspect that policy planning must address.

The charts in *Figure 8* show how fossil fuel use evolves in each scenario. Unabated fossil fuel use remains in the *Balanced, High Electrification* and *Decarbonised Gas* scenarios until the late 2040s. The *Rapid Progress* scenario achieves unabated phase-out by 2042. Fossil fuel use with carbon capture and storage continues in all scenarios.



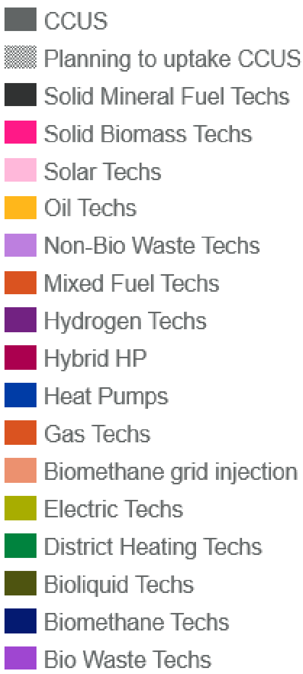


Figure 8: Breakdown of total existing annual heating demand by scenario and by technology type, 2020-2050, across all sectors

Heat pumps and other electric technologies have a prominent role

Figure 9 shows that heating technologies that use electricity as a fuel have a major role in all the decarbonisation scenarios. Heat pumps supply 12-20% of heating demand in 2030 and 33-38% in 2050. These technologies are available now and are the most cost-effective decarbonisation options for many heat users on a lifetime cost basis.

Heat pumps have a crucial role in decarbonising buildings. Buildings currently using oil tend to switch to heat pumps in all scenarios because of the favourable economics compared to the other available decarbonisation options. They also replace some fossil fuel boilers in the industry sector that supply medium and low-grade heat at temperatures up to about 200 °C. Heat pumps are also a prominent energy source for district heating networks in the scenario results.

Other electrification technologies also have a significant role, particularly in the industry sector. These technologies are the most economic decarbonisation option for many sites.

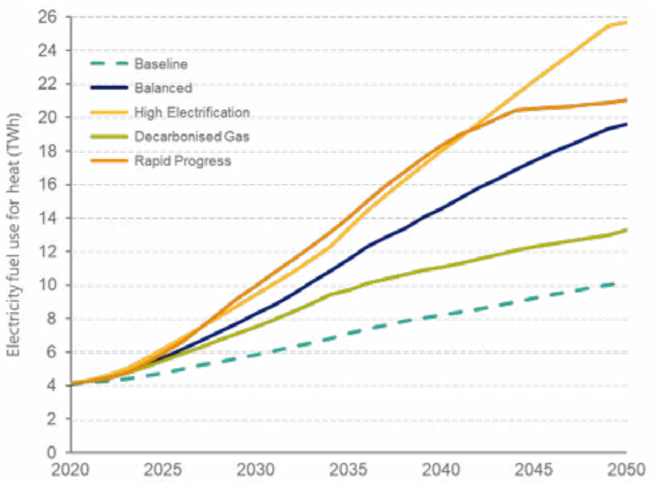


Figure 9: Electricity used for heat in each scenario

The decarbonisation of the electricity system is a crucial foundation for progress in the heat sector. As shown in *Figure 8* there are substantial increases in electricity use for heat in all the scenarios. This occurs along with increases in electricity use in the transport sector and from data centres. The deployment of renewable generation, flexibility measures and required infrastructure for the electricity grid must stay ahead of these demand increases to realise the full emissions benefits of these technologies.

District heating has substantial deployment potential

The modelling shows that significant potential for district heating exists in Ireland, suggesting that networked heat energy could meet approximately 50% of building heat demand. This potential includes the major urban centres in Ireland and the large regional towns, particularly those where the economics are more favourable because of the widespread use of oil heating.

Figure 8 shows the uptake of district heating in each scenario. We modelled district heating uptake based on small geographical areas, each containing 80 to 120 dwellings. Areas in urban settings are smaller, and in rural settings, they tend to be larger. For the uptake of district heating to happen in a small area, it must be cheaper than the fossil fuel options available to buildings. Those areas with high heat density, high-cost fossil fuels and available low-cost heat energy to supply the network have the most favourable economics. The modelling analysis uses some conservative assumptions that limit the uptake of district heating to an amount below the full potential. The maximum is limited to various percentages of building heat demand, excluding heat demand from industry. In the *Decarbonised Gas* scenario, the uptake is limited to 10% of building heat demand, in the *Balanced* scenario it is limited to 20%, and in the *High Electrification* and *Rapid Progress* scenarios it is limited to 30%.

Heat extracted from purpose-built combined heat and power generation and waste heat are the cheapest energy source for heat networks. Heat pumps and biomass are also widely used to meet the heat supply needs in the modelling where combined heat and power is not available. Geothermal heat is also considered a significant potential source for district heating in the medium term. As data limitations exist on the resource at depths >400m, complete modelling analysis is not currently possible; work is ongoing to close this gap[4]. Further work aimed at the complete characterisation of the suitability of the geothermal resource across Ireland will allow a better understanding of its potential for district heating at various locations. In addition, geothermal can provide opportunities for low-cost heat and inter-seasonal energy storage.

Sustainable bioenergy has an important role

Bioenergy meets a significant portion of heat demand in all scenarios. *Figure 8* shows 7-17% of heat demand is supplied by bioenergy in 2030 and a similar amount (5-16%) in 2050. All the available low-cost domestic bioenergy resources that are generated by other non-energy activities are used. Sawmill residues, waste wood and forest thinning, and harvest residues are used in biomass boilers in the agriculture and industry sectors to replace oil. Food waste is used to produce biomethane.

Energy crops also see significant uptake and use. The available land – the land that remains after supply of grazing and fodder for livestock, environmental and other competing uses are accounted for – is used in different ways depending on the scenario. In the scenarios where

[4] In the Baseline current policy measures are those from the Climate Action Plan 2019 that had existing implementing measures such as funding and planning or legislation in place by the end of 2020.

the available land is used to grow perennial energy crops, such as willow short rotation coppice, these resources are used in biomass boilers. Where the available land is used to grow a red clover and ryegrass mix, the silage produced is mixed with cattle slurry and used to create biogas and biomethane.

Table 2 shows the use of biomass resources in each scenario. All scenarios make use of the biomass available from the forestry by-products, food and other biodegradable wastes. The differences between the scenarios are based on land use for energy crop cultivation. The *Rapid Progress* scenario has the highest availability of domestic resources because of the assumption that there are additional land-use changes from beef farming to growing a low-cost red clover and ryegrass mix for silage for biomethane production. This scenario also allows biomethane use at sites currently using higher-cost and higher-carbon oil, making it more competitive and more cost effective in reducing CO_2 emissions.

The *High Electrification* scenario uses the available land to grow willow. The *Balanced* scenario also allocates some land to grow willow. These crops only become available later because of the current immature supply chain. However, over the long term, the crop produces more energy because of its higher per hectare energy density. Willow also has a more favourable upstream greenhouse gas emissions profile than biomethane produced from grass silage, although when slurry is added to the production process, the upstream emissions profiles for the two fuels are similar.

The use of the gas grid declines in net-zero scenarios

Figure 8 shows the differing roles of gaseous fuels across the net-zero scenarios. Three options are available:

- Biomethane is used for heating, either via grid injection or directly trucked to a site.
- Green hydrogen is supplied through the gas grid to heat and power users, which can be initially supplied through blending and/or through localised and dedicated hydrogen grids.
- Fossil gas carbon capture and storage is deployed at suitable industry and power sector sites and supplied through the existing gas grid.

Figure 10 and *Figure 11* show the current gas fuel demand and projected demand in 2050 for each scenario. All scenarios show a reduced role for the gas grid. Even the *Decarbonised Gas* scenario shows a reduction of approximately 25% from current levels by 2050. The other scenarios reduce grid connected gas use by around 60-75%.

This study investigates the potential role of green hydrogen as a decarbonising fuel option for both heating and for the power sector. The potential supply of green hydrogen is larger than the total Irish heat demand because of Ireland's sizeable offshore wind resource. However, the supply chain for green hydrogen is not yet mature, and its supply is likely to be limited in the early years. Hence, hydrogen fuel becomes available at scale in the scenarios during the 2030s. The industry sector uses hydrogen fuel in all scenarios, primarily to produce high grade and medium grade heat. In the *High Electrification* and *Rapid Progress* scenarios, hydrogen supplies 7-10% of industry fuel demand by 2050 (approximately 1.7 TWh). In the *Balanced* scenario, 17% of industry fuel demand comes from hydrogen by 2050 and 48% in the *Decarbonised Gas* scenario. In contrast, the use of hydrogen for space heating is limited, with only

Table 2: Total primary energy consumption (TWh) of biogenic fuels in 2030 and 2050, broken down by end fuel use, for each scenario.

Scenario	Wood chips / pellets		Biomethane / biogas		Other (including bioliquids and bioLPG)	
	2030	2050	2030	2050	2030	2050
Baseline	6.3	5.3	2.2	2.2	0.3	1.1
Balanced	5.5	7.5	2.8	2.4	0.4	1.1
High Electrification	3.7	6.6	1.1	0.1	0.1	1.1
Decarbonised Gas	3.5	3.4	4.6	2.0	0.4	1.1
Rapid Progress	4.2	5.4	8.2	7.5	0.4	1.1

the *Decarbonised Gas* scenario seeing significant uptake. The deployment of district heating and heat pumps substantially reduces the distribution grid's role. As gas use for space heating declines, this leaves fewer consumers to cover the fixed costs of the network, so they increasingly pay higher prices. This price effect further accelerates the move into other technologies.

Biomethane is available sooner than hydrogen but in more limited quantities. The resource estimates suggest that the available biomethane resource could be 4-8% of Ireland's current gas fuel demand. If changes to land use in agriculture were to occur and the freed-up land was used to grow a red clover and ryegrass mix for grass silage, then this could rise to 11% of current gas demand by 2030. Biomethane is initially prioritised for injection into the gas grid, but as it transitions to hydrogen, its use shifts to off-grid sites. The *Rapid Progress* scenario is the exception to this, where there is an emphasis on the direct use of biomethane at transmission-connected industry sites as well as industry sites outside of the gas grid. This is because a decision is made in the 2020s to curtail and decommission the gas distribution grid while maintaining and developing transmission networks for biomethane and hydrogen.

The *Balanced* and *Decarbonised Gas* scenarios also use biomethane primarily through grid injection. In these scenarios, the grid begins transitioning to hydrogen in 2035. This is within the lifetime of the anaerobic digestion technologies used to generate biomethane and shows the commercial uncertainties a grid injection biomethane supply chain would face in a scenario with accelerating deployment of hydrogen. As the gas grid transitions to hydrogen in later years, the use of biomethane declines. Support for off-gas grid use of containerised biomethane can mitigate these risks to the commercialisation of biomethane.

Fossil methane gas is also used with CCUS in several scenarios. By 2050, industrial sites with CCUS technologies use 1.7-4.4 TWh of abated fossil gas. We assume 90% of the emissions are captured. Negative emissions from Bioenergy with carbon capture and storage (BECCS) use at other industrial sites offset the residual emissions. The power sector also uses fossil gas with CCUS.

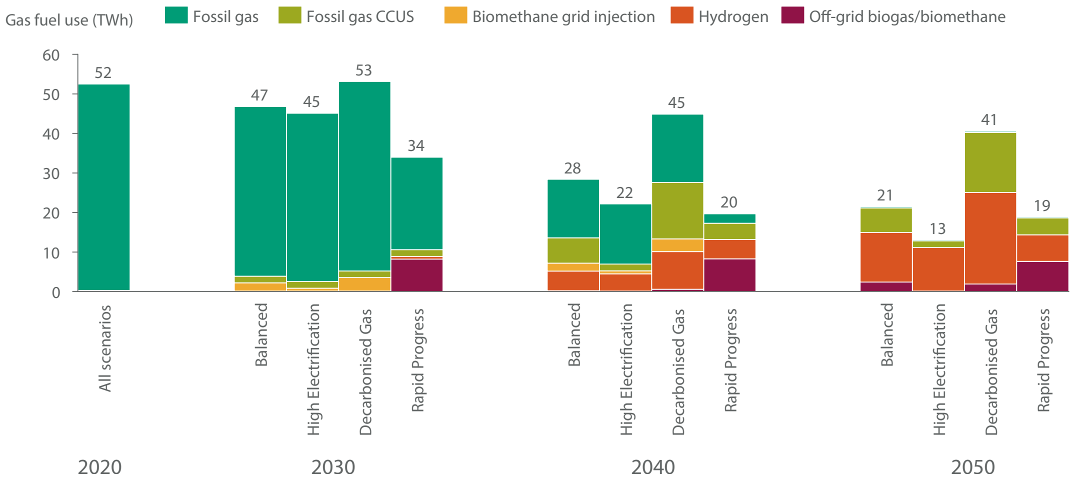


Figure 10: Total gas fuel use (TWh) in key milestone years, broken down by gas type, in each decarbonised scenario

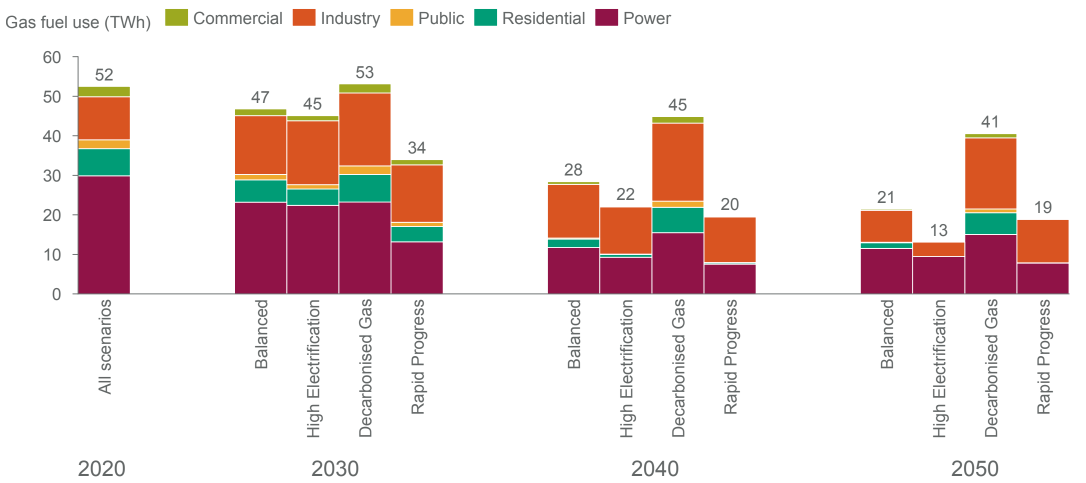


Figure 11: Total gas fuel use (TWh) in key milestone years, broken down by sector, in each decarbonised scenario

Carbon Capture, Utilisation and Storage

The energy system decarbonisation scenarios aligned with Ireland's objectives suggest that CCUS and greenhouse gas removal technologies are likely to be required [5], [6]. This work models the inclusion of CCUS, including technologies such as Bioenergy with carbon capture and storage (BECCS). Along with sustainable biomass fuels, BECCS allows CO_2 captured by plants to be captured and stored, providing a source of negative emissions.

Each scenario assumes differing deployment at the existing industry sites identified as having suitable potential, with differing levels of deployment assumed across scenarios. The use of the potential is aligned with the evolution of the energy system in each scenario and accounts for sites, such as cement manufacturers, that have process emissions that are difficult to abate by other means. The deployment timing is based on an assessment of the technology readiness levels and the current policy backdrop in Ireland. Sites that switch to electricity or hydrogen to fuel their heat demands are not suitable for CCUS and negative emissions may be required to offset emissions elsewhere in the energy system and in the wider economy or, in the case of a delayed transition, to claw back emissions that occurred before the technology was available. The consideration of these factors contributes to the difference in the quantity of CCUS abated emissions across the scenarios.

Figure 8 shows that 6-15% of heat demand in 2050 is delivered by heating systems that use CCUS abatement to manage emissions. The published background technical work identified 16 sites in Ireland's industrial sector where CCUS technology could be suitable. Centralised decisions are required to enable the deployment of the technology, and the variations in CCUS deployment across the scenarios represent a range of deployment ambitions.

Post-2040, we assume BECCS deployment in all scenarios. In *Decarbonised Gas*, *Balanced* and *Rapid Progress*, deployment of BECCS at industrial sites and in the power sector cause annual emissions to go negative in that sector. The heat technologies that use electricity benefit from the resulting negative emissions factor associated with negative electricity emissions. Conversely, in the *High Electrification* scenario, the power sector achieves net zero without BECCS. There are also fewer opportunities to deploy CCUS on industrial sites that have switched to electricity. Hence, the annual emissions remain close to zero in this scenario. The *Decarbonised Gas* scenario represents a high CCUS deployment scenario. By 2050, 16 sites install CCUS and BECCS technologies, total net emissions are -15 $ktCO_2$, fossil fuel reduces by 7 TWh and 1.5 TWh of biogenic fuels provide negative emissions of 1.3 Mt CO_2. *High Electrification* represents a low deployment scenario with three industrial sites installing the technology. These remaining sites use biomass fuels and some gas to meet their energy and process needs.

Capital investment required to deliver net zero

An additional 4.2-8.7 billion of investment is required to decarbonise the buildings sector in the scenarios examined. For the industry sector, an additional investment of €0.6-2.1 billion in low-carbon technologies is required. Investments are also required in hydrogen, district heat and electricity infrastructure. *Table 3* details the undiscounted investments estimated for various sectors and infrastructure options by scenario across the full horizon.

Table 3: Total capital investment required by scenario, for energy efficiency improvements (broken down by sector), heating technologies (broken down by sector), and renewable fuel production infrastructure. All costs are given in €bn, based on the total sum of in-year investments (not discounted).

Investment type	Baseline	Decarbonised Gas	High Electrification	Balanced	Rapid progress
Energy efficiency improvements					
Residential	0.39	2.04	1.86	1.95	1.85
Services	0.62	0.70	0.62	0.66	0.63
Industry	0.11	0.16	0.19	0.19	0.18
Heat technology					
Residential	20.16	27.37	23.79	27.48	25.73
Services	4.69	4.40	3.75	4.11	3.96
Industry	2.34	2.66	2.20	3.31	2.81
Infrastructure					
District heating infrastructure	0.04	2.61	9.53	5.94	9.67
Hydrogen infrastructure and production	0.00	23.07	2.24	6.21	3.15
Electricity infrastructure	10.51	16.27	25.41	21.01	23.87
CCUS infrastructure	0	1.55	0.62	1.04	1.30
Total	**38.86**	**80.82**	**70.21**	**71.90**	**73.15**

Ongoing fuel costs

Figure 12 shows the annual fuel costs for all sectors, including the residential and industrial sectors. Households see a long-term benefit from decarbonisation investment, with all scenarios showing lower household fuel spend than in the *Baseline* across the whole time period. The higher efficiency of low-carbon technologies they install means less fuel is needed to satisfy their heating demand. Conversely, the industry sector faces cost and competitiveness challenges in decarbonisation scenarios. Currently, most industry sectors use low-cost gas to meet their heat demand needs. While low carbon and renewable technologies are available now, these are generally more expensive to run. So too are those technologies that become available later. Green hydrogen is approximately twice as expensive as fossil gas, and the efficiency penalty from carbon capture technologies also increases fuel costs.

How do the total costs of decarbonisation compare?

We undertook a cost-benefit analysis as part of the work to understand how the scenarios compare. The method is aligned to the Public Spending Code. It takes a societal point of view by incorporating socio-economic factors, such as a suitable social discount rate, and environmental externalities in determining net present cost (NPC). The analysis included direct costs and benefits caused by technologies, infrastructure, fuels and some additional costs related to other environmental externalities. The key inputs are:

- Plant and equipment capital investments (including that provided by policy support, such as grants).
- Associated energy networks capital investments.
- Variable and fixed operating costs (excluding fuel and energy).
- Long-run variable energy costs (variable wholesale and network costs, including district heating).
- Carbon costs (based on traded shadow prices of carbon provided in the Public Spending Code).
- Damage costs of non-greenhouse gas pollutants (PM, NOx, SOx, VOC costs) as set out in the Public Spending Code.
- Upstream emissions from biomass fuel use.

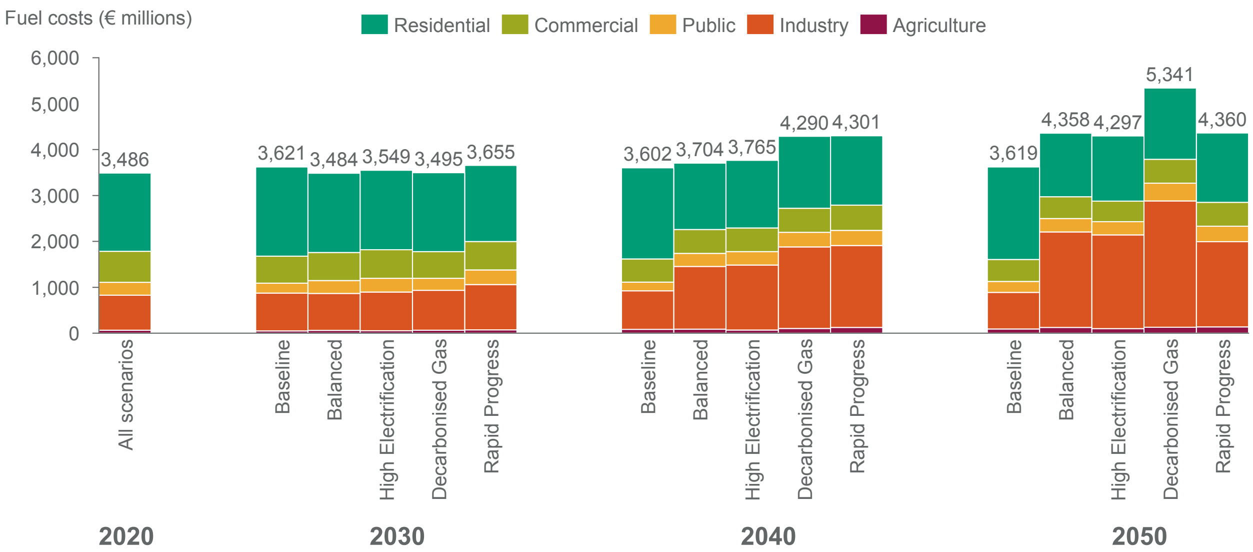


Figure 12: Total annual ongoing fuel costs for key milestone years (€2019 million)

Figure 13 below presents a summary of the results of the economic cost-benefit analysis, shown in real 2019 terms, discounted to 2020. Three of the four decarbonised scenarios have a lower NPC compared to the *Baseline* scenario. The shadow cost of the additional emissions produced in the *Baseline* scenario is the primary driver of the higher costs. The costs of the *High Electrification* scenario are 6.3% lower than the *Baseline* scenario, with the *Balanced* and *Rapid Progress* scenarios showing total discounted costs that are 1.4% and 0.3% lower. The *Decarbonised Gas* scenario has the highest cost of all the energy systems, 4.5% higher than the *Baseline* scenario.

Hydrogen and CCUS infrastructure investments, the higher cost of installing hydrogen technologies and the relatively high price of green hydrogen fuels are the main differences that cause the *Decarbonised Gas* scenario to have the highest overall costs. These factors, and the speed of decarbonisation, also influence the costs in the *Rapid Progress* scenario. The technology and infrastructure investment occur earlier and benefit less from the discounting effect than other scenarios. As shown in *Table 3*, the costs in the *Rapid Progress* scenarios are comparable to other scenarios before the costs are adjusted for the future value of money. The *High Electrification* scenario has the lowest deployment of CCUS and hydrogen use. It also sees some benefits from the increased efficiency of electric heating, which offsets the higher unit costs of electricity, mainly where heat pumps are used.

The declining role of fossil fuel in the net-zero scenarios reduces CO_2 emissions costs and the costs associated with aerosol emissions that reduce air-quality. However, the combustion of solid biomass in the net-zero scenarios offsets some of the air-quality benefits. The *Rapid Progress* reaches net zero sooner and therefore emits less CO_2 overall. It also gains from emissions removals by using BECCS from the mid-2040s. This leads to fewer emissions overall and a lower cost of carbon. Conversely, the *Decarbonised Gas* scenario has the highest emissions costs of the other decarbonised scenarios due to the higher cumulative emissions in this scenario. The shadow price of carbon greatly influences the overall outcome. An overall price increase, as well as a faster rise in the earlier years, would improve the relative cost outcome of the scenarios that decarbonise quickest.

In the Rapid Progress scenario, an additional NPC of €3.8 billion would be needed in subsidies outside of the energy sector to support the production of biomethane at a competitive price and in the required quantities to drive the uptake of biomethane utilised in the industry sector. As these costs are not in the energy sector, they are not included in the CBA results presented here.

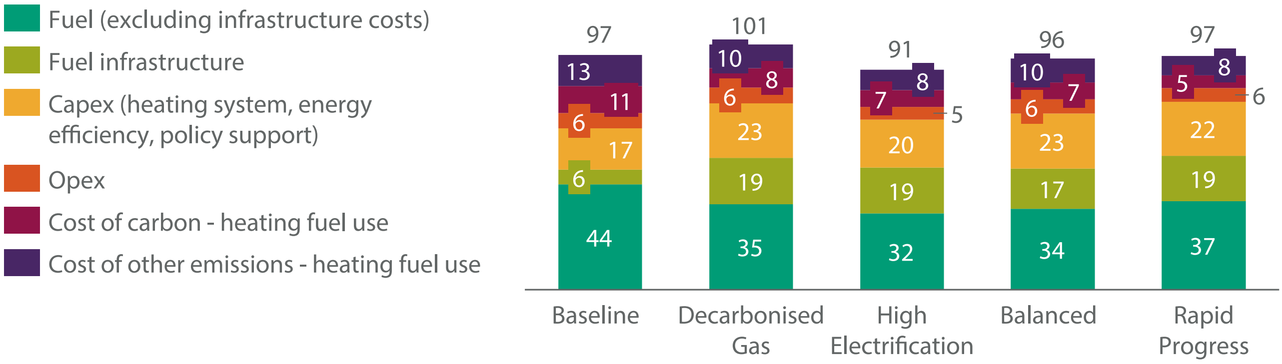


Figure 13: Economic Cost-Benefit Analysis (CBA) – summary of net present costs (€bn) across scenarios

Key Actions

The study has highlighted several areas where policy can act to deliver on the heat decarbonisation opportunities.

Three categories are explored here; the study helps to identify:

- Actions that can be taken now to contribute to our decarbonisation targets.
- Some technology pathways require decisions now to provide market certainty and avoid delayed action.
- Actions that need to be immediately investigated further to support the next wave of policy effort.

In some cases, the findings reinforce measures already included in the 2021 Climate Action Plan. In others, they provide direction as to the prioritisation of effort and the need for extended measures through the lens of decarbonising heat as quickly as possible and ultimately reaching net-zero emissions from heat. In acting and making the necessary decisions, it will be essential to understand areas of interdependency where a choice in one sector or for one technology could affect future decisions or policy options.

In addition to the urgency of implementation, longevity and continuity of policy are essential to achieve significant replacement of high-carbon heating technologies. Given the long lifetime of heating systems (15+ years), less than 8% of existing systems are replaced each year, so most homes and businesses will purchase new heating systems only twice before 2050. In addition, the supply chains for heating and energy efficiency are still developing, particularly in the residential and commercial sectors, and comprise many small businesses and some larger enterprises that deliver a broad range of services. For these reasons, stable policies with relatively long lifetimes are likely to be more effective at promoting renewable system adoption than policies that aim to achieve radical change within only a few years.

Act Now:

Actions that can be taken now

Plan and prioritise district heating deployment – target the regulatory, planning and financing barriers to reduce the implementation cost and timelines for district heating projects.

District heating technologies are available now and have been deployed at scale in other countries. The modelling shows that heat network infrastructure can be built and supplied by various technologies and fuels at a cost that competes with fossil fuel options. Low-carbon heat sources, supplied via district heating networks, could meet up to 50% of building heat demand.

The primary barriers to uptake relate to planning, regulation and financial factors. Policy frameworks that put district heating infrastructure delivery on a similar footing to other energy infrastructure can alleviate many of these barriers. State-owned companies that deliver gas and electricity networks can access low-cost financing and have the specialised technical and centralised skills and tools to deliver these infrastructures at scale. Replicating these conditions for district heating infrastructure can drive significant deployment.

Policy, regulation and planning that supports heat extraction from newly built power stations to supply heat networks can further improve the economics of district heating. Opportunities for heat extraction from power stations and waste heat recovery from industrial sites, geothermal sources and low-grade heat from data centres to feed into district heating schemes should also be encouraged.

Shift the emphasis of building decarbonisation policy to elimination of fossil fuel heating.

Current support schemes apply the fabric-first principle. Its application asks consumers to use available fabric technologies and budget to reduce heat demand before installing a heating system. Policy at an EU level supports this approach and captures the sentiment in the phrase 'energy efficiency first.'

However, this approach is not guaranteed to be consistent with the rapid decarbonisation needed to meet the goals of the Climate Action legislation. It is not financially viable for a large proportion of consumers in the analysis[7] and consumers do not favour it in the consumer choice modelling. Even in scenarios that model grant supports of 60-80% of the capital cost, consumers still do not install the more extensive fabric measures in large numbers. Model outcomes suggest consumers are likely to prefer to install the low-cost and low-hassle fabric options, such as draught-proofing, roof insulation and cavity wall insulation, in combination with a low-carbon heat supply technology, such as an electric heat pump. Heat pump technology is available now, and they are prominent in all scenarios, including in the *Rapid Progress* and the *Decarbonised Gas* scenarios. The more expensive and challenging fabric options, such as floor and solid wall insulation and high-efficiency glazing, are chosen much less frequently. Fabric is instead used to improve the payback on the heating system investment and to ensure the suitability of a building for low-temperature heat sources (heat pumps). This approach puts decarbonisation first, with fabric retrofit in a supporting role, leading to faster decarbonisation of heat.

These results suggest that realigning the fabric-first principle with legislative requirements for deep and rapid emissions cuts can deliver enhanced uptake of low-carbon technologies and fuels. They also suggest that retrofit activity targets can be more aligned with emissions reduction goals by focusing on the heat supply rather than on the final building energy rating a building achieves. Scheme design that focuses on meeting the minimum levels of fabric performance to support a switch away from fossil fuel heating sources, or includes only fabric measures that offer a short payback period when combined with the low-carbon heating system, is likely to see more uptake, require less investment and see more emissions cuts. Consumers may then make additional fabric improvements in the future when higher fuel costs or lower fabric efficiency costs provide more attractive paybacks, and when consumers have access to further investment budgets.

Improvements in building thermal performance remain an important policy goal from the perspectives of health, wellbeing, fuel poverty and comfort. However, policies associated with building regulations and planning permission (triggered by building works) may achieve better thermal performance than with decarbonisation (triggered by heating system replacement).

Raise awareness of the competitive low-carbon heating options available for services sector buildings and industry; address the non-financial barriers preventing uptake.

The services sector has a strong uptake of renewable heating technologies (heat pumps, district heating and biomass fuels) in all scenarios, including the *Baseline* scenario. The results suggest that renewable and low-carbon options already make economic sense for many consumers. Heat pumps, district heating and biomass fuels all see strong uptake in the services sector. In the industry sector, several technologies are competitive, particularly for those industry sites using oil. However, this uptake is not yet happening to the same degree because of other non-financial uptake barriers facing organisations in the enterprise sectors, such as lack of awareness, split incentives between landlords and tenants, the low proportion of energy costs in total business operating costs and centralised corporate decision making on energy investments.

Awareness-raising campaigns and other promotional activities can help bring the opportunities into view. Streamlined, trusted and accessible support and advice can help build demand and support the services sector consumers to navigate the early-stage supply chains for some of these technologies. The leadership role of the public sector can help build the supply chain capacity in Ireland. The Climate Action Plan's commitment to stop the installation of fossil fuel heating systems from 2023 will help drive this.

As with the residential sector, fabric upgrades have an important role in supporting delivery of low-carbon heat supply technology in the commercial and public services sectors. Scheme design that focuses on meeting the minimum levels of fabric performance to support a shift away from fossil fuel heat supply is likely to be less complex, see more uptake, require less investment and deliver more (and faster) emissions cuts.

Implement nationally appropriate sustainability governance and market development activities to deliver the bioenergy potential aligned with economy-wide emission reduction goals.

Bioenergy meets 7-16% of heat demand in all scenarios in 2030 and 2050. Domestic resources and imported biomass fuels are primarily used in solid and gaseous forms, with some small amounts of bioliquids in some scenarios. The resource assessments for the biomass feedstocks consider upstream greenhouse gas emissions and other important sustainability aspects, such as biodiversity. Hence, the resource estimates are based on specific good practice approaches to their cultivation, harvesting, collection and use, which help to minimise overall climate impacts. For example, only energy crops that are grown on environmentally suitable land with a minimum of additional nutrient inputs are available for the model. Energy crops grown in ways that depart from these assumptions risk causing environmental damage and more greenhouse gas emissions in the land use and agricultural sectors.

Therefore, robust and nationally appropriate sustainability standards and governance are required. EU sustainability governance only applies to larger sites. Its direct transposition into Irish law means that governance rules would not apply to the large proportion of bioenergy use in Ireland below the minimum EU size threshold. The EU legislation allows countries to set size thresholds that are aligned with their individual circumstances. Such nationally appropriate sustainability governance measures and other market development supports can provide a foundation for biomass supply chains to contribute to their full potential while reducing the risk of emissions increases in the agricultural sector and from land use change.

Develop policy frameworks that allow the costs and benefits of renewable and low-carbon gases to be shared across all gas customers. Enable off-grid heat users that currently use higher-cost and higher-carbon fossil fuels to access biomethane outside of the grid.

While the resource estimates for feedstocks that can produce biogas are lower than previous estimates, what is available is widely used to produce biomethane in the scenarios. The cost of off-grid biomethane is competitive with oil. Grid-injected biomethane is competitive with other options when it makes up a low proportion of total gas fuel in the grid and when the costs and benefits are shared among all gas consumers.

The cost of grid-injected biomethane fuel is spread across all gas consumers, so each consumer sees a slight increase in price and a small decrease in emissions. Consumers pay for the costs of biofuels in transport and renewable power in this way. However, if biomethane costs and benefits are seen by an individual consumer, the fuel becomes significantly less competitive against gas and the other low-carbon options available. A similar loss of competitiveness occurs if the proportion of biomethane in the grid grows.

Biomethane is typically more competitive in off-gas grid applications where it is transported directly to an industry site to replace oil. The relative carbon savings are also higher when used at these sites. Policy frameworks that seek to support the development of biomethane should allow these routes to compete with grid injection options.

Deliver plans for renewable deployment on the electricity grid.

The analysis shows that electricity use for heating has a prominent and increasing role in all the scenarios examined, with particularly strong growth post-2035. Delivery of renewable capacity and supporting grid flexibility must stay ahead of demand growth to realise the benefits of emissions savings from this demand-side electrification of heat. The high-resolution electricity modelling shows power sector emissions reducing by about 50% by 2030 (relative to 2018), while demand increases by 61-69% in the same period – driven by data centres, electric vehicles and heat electrification. The power sector modelling sees 10-11 GW of installed wind capacity by 2030 to meet a renewable electricity percentage of at least 70%. The Climate Action Plan is targeting an 80% renewable electricity share by 2030, and its delivery will further enhance the heat sector emissions savings.

Include spatial planning in policy considerations.

The modelling shows that there are spatial variations in technology uptake. Rural oil-heated buildings favour heat pumps, district heating is deployed in cities and towns, and bioenergy uptake is prominent at sites located away from the gas grid. Spatial factors are also important for electricity infrastructure to ensure that the grid is ready for electrified heat demands. Policy approaches that account for these patterns can avoid sub-optimal outcomes which could arise due to the provision of competing incentives for alternative low-carbon technology options.

For example, public services heat demands are significant anchor demands that improve the economics of district heating networks. Should the public sector respond to competing policy signals and install other low-carbon technology options, the opportunity for district heating is likely to be diminished in all sectors.

Heat extraction from newly built power stations is among the lowest-cost energy sources for heat networks. Policy signals that seek to co-optimise the location of power generators to meet the power system's needs and district heating demands can maximise these low-cost heating opportunities.

Provide long term and stable policy signals.

Technology changes in the heat sector happen gradually due to the turnover rate of energy technologies as they reach the end of their useful life. The retirement of existing technology is a critical decision point where homeowners and businesses can move to a low-carbon option. Clear policy signals on continuing support and implementation timelines for technology adoption can influence the uptake of low-carbon systems. Policies with long-term plans and committed lifetimes can have the most significant impact and provide certainty and stability to aid the development of robust supply chains.

Decide Now:

Decisions required now

The role of negative emissions in achieving economy-wide net-zero goals by 2050.

The anticipated decarbonisation actions and technological improvement may not be enough to achieve carbon neutrality given the challenge of eliminating emissions in 'hard to decarbonise' parts of industry and agriculture. In the context of government-approved carbon budgets and sector emissions ceilings, this implies that some sectors are likely to need to achieve negative annual emissions to meet the goal of economy-wide carbon neutrality. The routes to negative emissions in Ireland imply decisions about land use, fuel use, CCUS and the role of bioenergy and direct air capture. These decisions have onward implications for factors such as:

- **The amount of energy supply available from energy crop cultivation in Ireland.** For example, forestry planting that is significantly higher than the current 8,000 hectares per year target is likely to limit the potential for planting energy crops that produce biomethane and solid biomass fuels.
- **The amount of negative emissions that BECCS can deliver.** A transition to zero-emission fuels such as hydrogen and renewable electricity means there will be less CO_2 available for capture (where a bioenergy alternative might have been installed), and this may limit the opportunity to achieve economy-wide net zero by 2050. However, waiting for BECCS technology may result in higher peak annual and total cumulative emissions overall. Land use options also affect how much bioenergy may need to be imported.
- **The demand for electricity and renewable electricity generation capacity.** Direct air capture technologies add to the demand for electricity, which requires additional renewable electricity production and competes with hydrogen production potentials.

A policy determination on the role of negative emissions to achieve economy-wide carbon neutrality by 2050 will help align onward policy decisions across land use, CCUS and renewable electricity generation requirements.

Development risks for negative emissions technologies should be considered on an ongoing basis as part of policy considerations.

Plot a path for carbon capture, utilisation and storage.

Carbon dioxide removal is a well-established technology in some industrial sectors, including hydrogen production, fossil gas processing and biomethane upgrading. However, carbon capture technologies on power and heat generation plants are expensive due to the high energy penalty associated with the CO_2 capture process and the low CO_2 content in the flue gas. As a result, despite few demonstrations worldwide, CO_2 capture processes on power and heat generation are still awaiting large-scale deployment globally. Technical work carried out as part of the National Heat Study outlines the progress that has been made towards deploying the technology at scale. Should Ireland wish to have the option to deploy this technology long term, then advanced planning around the role of CCUS and BECCS in Ireland is needed. Decisions are required on where and how the clustering of sites and infrastructure might be achieved. In order to facilitate the deployment of CCUS in Ireland, policy must address regulatory aspects related to CO_2 storage (such as liability, monitoring requirements, ownership) and business models, as well as financing mechanisms. In addition, investigation of emerging applications for the utilisation of CO_2 (such as concrete curing, green cement, synthetic fuels) should be encouraged.

The role and source of biomass fuels, and in what quantities, are also important factors to consider. This can provide certainty to infrastructure developers about the scale of CO_2 volumes to be transported and aid the development of business models for long-term operation. Mechanisms to encourage awarding negative emissions from BECCS and other NETs in line with recent developments in other countries should also be explored.

Timetable for fossil fuel phase-out.

To achieve a reduction to zero, heat consumers must only choose renewable and low-carbon options (such as electricity, bioenergy or green hydrogen-based heating sources) after a certain point in time. Technology life determines the latest date that this must happen. Fossil fuel technologies used for space and water heating have lifetimes of approximately 15 years. Hence, all consumers deciding how to heat their buildings from 2035 must choose a renewable or low-carbon option for an endpoint of net zero to be achieved by 2050.

In the industry sector, technology lifetimes are around 25 years. To reach zero by 2050, while getting the most out of their heating technologies, the industry sector would need to begin phasing out fossil fuels as early as 2025. However, this pathway likely presents competitiveness challenges for the industry sector and a large-scale phase-out of fossil fuels is unlikely in the near term. Pushing back the phase-out date would require early retirement of some systems to achieve the 2050 target.

If the emissions cuts from heat energy are to stay within the proposed carbon budget limits, then the move from fossil fuel will need to begin before 2025. If heat-using sectors are to carry a larger share of the decarbonisation target beyond a pro rata share, then fossil fuel phase-out must speed up even more.

For the industry sector, clear policy guidance on the future role of CCUS, the gas grid and the plans for the electricity grid and market can guide the investment decisions. For the buildings sector, decisions on the policy mix to drive decarbonisation are needed to accelerate investment in decarbonisation technologies and fuels.

The future role of the gas grid.

The National Heat Study has examined the role of green hydrogen in heating and included it as a decarbonising fuel for the power sector. However, its supply is likely to be limited until after 2030. The analysis shows that waiting for the deployment of green hydrogen leads to higher cumulative emissions overall across scenarios. Other technology options (heat pumps, district heating etc.) are available now to heat buildings, and many industry sites can also decarbonise by other means. Hence, in most of the decarbonisation scenarios studied, hydrogen has a lesser role.

Biomethane is available in moderate quantities and in the near term. However, it is not available in large enough quantities to bridge the emissions deficit to other scenarios until hydrogen becomes available in larger quantities. A larger role for biomethane is possible in the context of a policy decision that reduces the land requirement for the national herd. A lesser role is also possible if policy seeks to use available land for other energy crops or forestry and other sequestration options. Biomethane can also be deployed outside of the gas grid.

The gas distribution grid has a limited role in the decarbonisation scenarios. The deployment of district heating and heat pumps reduce the demand for gas. As gas use for space heating declines, it leaves fewer consumers to cover the fixed costs of the network, so they increasingly pay higher prices. This price effect further accelerates the move toward other technologies. Policy planning is required to limit the negative impacts of this transition for gas grid stakeholders.

The gas transmission grid sees reduced but significant demand from power and industry sectors. The scenarios examined include a role for a separate hydrogen grid to supply low-carbon fuel and a methane grid to supply sites that use CCUS to abate their emissions. A comprehensive government plan would need to be developed if this scenario was to be pursued and would need to address aspects such as:

- Alignment with the role envisaged for CCUS to achieve carbon neutrality by 2050.
- Advance development of hydrogen governance and regulation.
- Uncertainties on the additionality of green hydrogen and how renewable resources may be prioritised for hydrogen production or power generation.
- A transition plan from methane to hydrogen that avoids stranding biomethane assets and supply chains.

The role of secondary heating in the residential sector.

Solid fuels such as coal and peat used in stoves, ranges and open fires produce significant emissions (circa 1.6 $MtCO_2$ per annum). Many people living in rural Ireland use solid fuels to provide a large portion of their heating demand. This can keep fuel bills low, increase comfort and reduce reliance on oil as a primary heating source. But it comes at the expense of reductions in air quality in homes, towns and cities. Reducing the use of fossil fuels burnt in the home for heat has both climate and health benefits.

However, removing secondary heating as a condition of wider decarbonisation action in a home may cause reductions in the uptake of the necessary measures. Phasing out this activity or replacing it with low-carbon options, such as sustainably sourced and certified firewood, can deliver CO_2 savings quickly. Policy can explore the role of secondary heating in enabling the uptake of heat pumps and other low-carbon options. In any event, policy must find a pathway to eliminate the in-home use of coal and peat for heating to reach net-zero emissions – and early wins will contribute significantly to reducing cumulative emissions.

Investigate Now:

Actions for immediate further investigation

What are the preferred routes for achieving net zero in the electricity sector, and what role has demand-side flexibility?

The National Heat Study has modelled several routes to net zero in the power sector by 2050, including the deployment of green hydrogen fuel with hydrogen-ready gas turbines and BECCS. These fuels and technologies decarbonise the conventional generation required for the security of electricity supply when variable renewable electricity is less plentiful. Identifying the opportunities and challenges of decarbonising the conventional generation asset base is a pressing policy area given the scale of electricity demand growth expected over the coming years and decades.

The availability of BECCS and CCUS require CCUS infrastructure to be deployed and sufficient availability of sustainable biomass fuels. Depending on the volumes required, Ireland may need to import this bioenergy. Suitable sites in Ireland also need to be identified. The need for CCUS technology depends on the policy decisions regarding the role of these technologies in achieving economy-wide carbon neutrality. Hydrogen-fuelled gas turbines is another route to decarbonisation. The deployment of green hydrogen relies on the availability of wind power capacity, both offshore and onshore. Further work is needed to understand how using wind for hydrogen production interacts with the electricity system's needs, and if the capacity can be deployed quickly enough to meet the total requirements. Further work is also required to examine geological storage options and what impact ammonia storage may have on the emissions ceilings for these gases. Other low-carbon power generation options not examined as part of this work may also have a role.

Additional investigation is also required to understand the electricity system benefits that may accrue from large co-generation plants serving heat and power markets flexibly. Grid-connected electrolysers can produce hydrogen during high renewables and low-cost electricity. The fuel can be stored for long periods of time and can be combusted in gas turbines to generate energy during periods of low renewable availability. Industry sites could also benefit from this business model. For example, industry sites that electrify their heat demand, install thermal storage capacity and maintain their power generation capacity can both reduce their average electricity costs and receive revenue for the electricity market. These price arbitrage opportunities may be significant on a small, highly renewable electricity system. Large-scale district heating systems with heat storage can also interact with the power system in this way. Storage with combined heat and power generators and heat pumps can all act together to optimise heat and power production.

Further work is required to understand the benefits and costs of the interactions at a site and system level. Further investigation is also needed to understand how current market and grid operation rules would need to change to facilitate such systems and market interactions, and the impacts on energy consumers.

How does the economy develop in deep decarbonisation scenarios?

The National Heat Study analysis uses some macroeconomic inputs as part of the modelling. However, no further iteration has taken place to understand how the deep decarbonisation scenarios examined here might impact overall economic growth. The ongoing energy cost increases for industry, energy cost reductions for buildings and a large amount of capital investment in all sectors are likely to have a significant economic impact. Further work is needed to understand how deep decarbonisation pathways affect economic activity, exchequer funds and energy demand. Consideration should be given to how the counterfactual of remaining a high-carbon economy would affect foreign direct investment, the ability to attract finance, ongoing exchequer costs, and litigation that would result from non-compliance with international and national legislation.

How do the decarbonisation pathways perform in low probability / high impact events?

The modelling analysis carried out in the National Heat Study focuses on exploring the pathways to net-zero emissions for heat. While the assumptions around technology and infrastructure sizing consider extreme peaks in demand, the work has not explored how the scenarios perform in extreme weather events. For example, in a highly electrified scenario, prolonged periods of low temperatures could cause security of supply. Low temperatures can reduce heat pump efficiency when they are working hardest to maintain internal temperatures. Wind speeds are often below average during these freezing spells. More work is needed to understand how technology deployment can be configured to manage the danger of power cuts and deliver backup heating options if they occur.

How can new business models help the industry sector meet the competitiveness challenges of decarbonisation?

The unit costs of low-carbon and renewable fuels for the industry sector are typically higher than the fossil fuel options they currently use. Industry sites that do not alter their energy use to avail of lower energy prices are fully exposed to the high average unit costs of low-carbon fuels. New business models that allow industry sites to interact more dynamically with energy markets can allow them to consume more renewable energy during lower price periods.

How can the delivery of green hydrogen be accelerated and its cost reduced?

The potential for green hydrogen is far greater than Ireland's energy demand. It can be used as a fuel for heat, power and transport and has many non-energy uses. The National Heat Study analysis examined the role of hydrogen in the heat sector and included it as a decarbonising fuel for electricity generation. However, green hydrogen is unlikely to be available at scale until the 2030s and likely to be more costly than other decarbonisation options. These factors limit the role of hydrogen in the heat sector.

Policy and research efforts that can hasten the deployment of green hydrogen and lower its cost can enable the fuel to play a larger decarbonising role. The ongoing research efforts are focusing on reducing electrolysis costs, enhancing how flexibly they can operate and improving the overall efficiency to help reduce the cost of production. The absence of suitable geological storage options increases the costs of hydrogen in Ireland. Further investigation into the availability of suitable geological storage in Ireland and into the development of liquid storage technologies could help lower the storage cost component of hydrogen fuel.

Within the 2020s, there may be a role for the initial development of green hydrogen with dedicated wind generation in parts of the country with limited electricity grid. For example, in the northwest of Ireland, access to the electricity transmission grid is constrained, but access to the gas grid is not. The generation of hydrogen to blend into the gas grid, using lower-cost onshore wind in locations where wind farms achieve high load factors, is a potential early deployment route. Alternatively, trucks or dedicated pipelines can transport hydrogen produced in these areas for use in transport or industry as pure hydrogen.

Glossary

TERM	DESCRIPTION
BECCS	Bioenergy with carbon capture and storage
CCUS	Carbon capture, utilisation and storage
DECC	Department of the Environment, Climate and Communications
GDP	Gross Domestic Product
GW	Gigawatt
$KtCO_2$	Kilotonnes of carbon dioxide
LPG	Liquefied petroleum gas
$MtCO_2$	Megatonnes of carbon dioxide
NEMF	National Energy Modelling Framework
NET	Negative emission technologies
NPC	Net present cost
SEAI	Sustainable Energy Authority of Ireland
TWh	Terawatt-hour (one million megawatts per hour)

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