Energy for generations

For a clean, secure energy future

Ireland's pathway to a net zero energy system by 2050

Contents

Foreword

Together, the electricity sector has delivered great progress along Ireland's pathway to a net zero energy system.

Already, there is more utility-scale renewable generation capacity connected to the Irish electricity system than our peak electricity demand of over 6GW. From a standing start only a few years ago, the system now benefits more than 2GW of solar power capacity – including from more than 150,000 rooftop installations. Electricity storage capacity has grown almost four-fold in recent years to over 1GW.

Customers and communities are taking advantage of the successful smart meter roll out and the opportunity to play their part in the clean energy transition. Our lifestyles are becoming more electrified and, correspondingly, less carbon-intense, with over 195,000 EVs now on Ireland's roads and around 170,000 heat pumps in Irish homes and businesses.

This is tremendous progress and a great foundation for building further and faster.

At ESB we continue to focus on delivery. 2026-2030 will see unprecedented investment in the electricity network, as set out in the PR6 programme – supporting economic growth and social development with increased capacity and connections, strengthening resilience, and enabling low-carbon technology adoption. This will be accompanied by an extensive buildout of renewable generation by ESB and others, as Ireland begins to unlock its offshore wind potential.

Taking our national plans as a starting point, this new ESB report sets out a vision of a 2050 energy system with very high levels of electrification powered by indigenous renewable electricity, supported by storage, and backed up by low-carbon dispatchable generation.

ESB has a central role to play in ensuring that this vision becomes reality for a growing, thriving Ireland. We understand how fundamental the electricity sector is to the delivery of economic growth, housing and social progress, and to the development and decarbonisation of sectors like transport, heating and industry.

While the external context is continually evolving, we remain confident that ESB's strategic objectives – decarbonising electricity, delivering resilient infrastructure, and empowering customers and communities – are essential to support the successful delivery of our national climate, economic and social development plans.

Paddy Hayes
Chief Executive ESB

Partnerships

ESB was supported in the development of this report by MaREI Research Centre, University College Cork, who carried out modelling of the 2050 energy system, and by management consultancy AFRY, who provided support in compiling both ESB's own Net Zero 2040 Pathway and the vision for Ireland's journey to net zero by 2050 presented here.

MaREI Energy · Climate · Marine

AFRY

The vision for our future energy system sees renewable power as the dominant energy source.

Ireland's energy system in 2050: At a glance

Our energy system encompasses all the infrastructure, processes and technologies involved in producing, delivering and consuming energy across the country.

One key way we use energy is in the form of electricity, which is increasingly generated from renewable sources like wind or solar power. In areas such as heat or transport, energy has traditionally been sourced directly from fossil fuels. As we move to decarbonise our economy and society over the coming decades, however, clean electricity will play an ever greater role in powering these sectors too.

In Ireland and across Europe, governments have set binding targets to reach net zero carbon emissions by 2050. ESB has set itself the ambition to become net zero by 2040, as a decarbonised electricity system is the essential foundation to reach our national 2050 goal. Placing the customer at the heart of this transition will be key.

Our vision for the future energy system focuses on six interrelated areas:

Whole energy system

To achieve net zero in our energy system by 2050, it will be vital to take a holistic view of the system as a whole – from planning, markets and capability, to customer engagement and other cross-cutting areas.

Electricity system

The vision for our future energy system sees renewable power as the dominant energy source, with demand regularly met by wind and solar generation. Making this happen will require new system operation practices, streamlined planning processes, policies to support an expanded and more resilient grid, and intelligent market design.

Flexibility, resilience and security of supply

A renewables-dominated electricity system will need additional measures to match the production of energy and its consumption, and to ensure security of energy supply during times of peak demand and/or when renewable power is less available – for example, by using demand response, energy storage systems of varying durations, and deploying new system services.

Industry

Industrial customers must be supported in the transition. Policy, regulation and supports can aid with implementation of technologies like electric heat pumps or boilers. Solutions such as carbon capture and storage may be needed to reduce emissions in hard-to-abate sectors.

Transport

By 2050, transportation will be dominated by low-carbon alternatives such as electric vehicles, public transport, and active travel. This transition must be customer-centred and will require significant investment and planning in infrastructure, innovation and supporting policies.

Heating

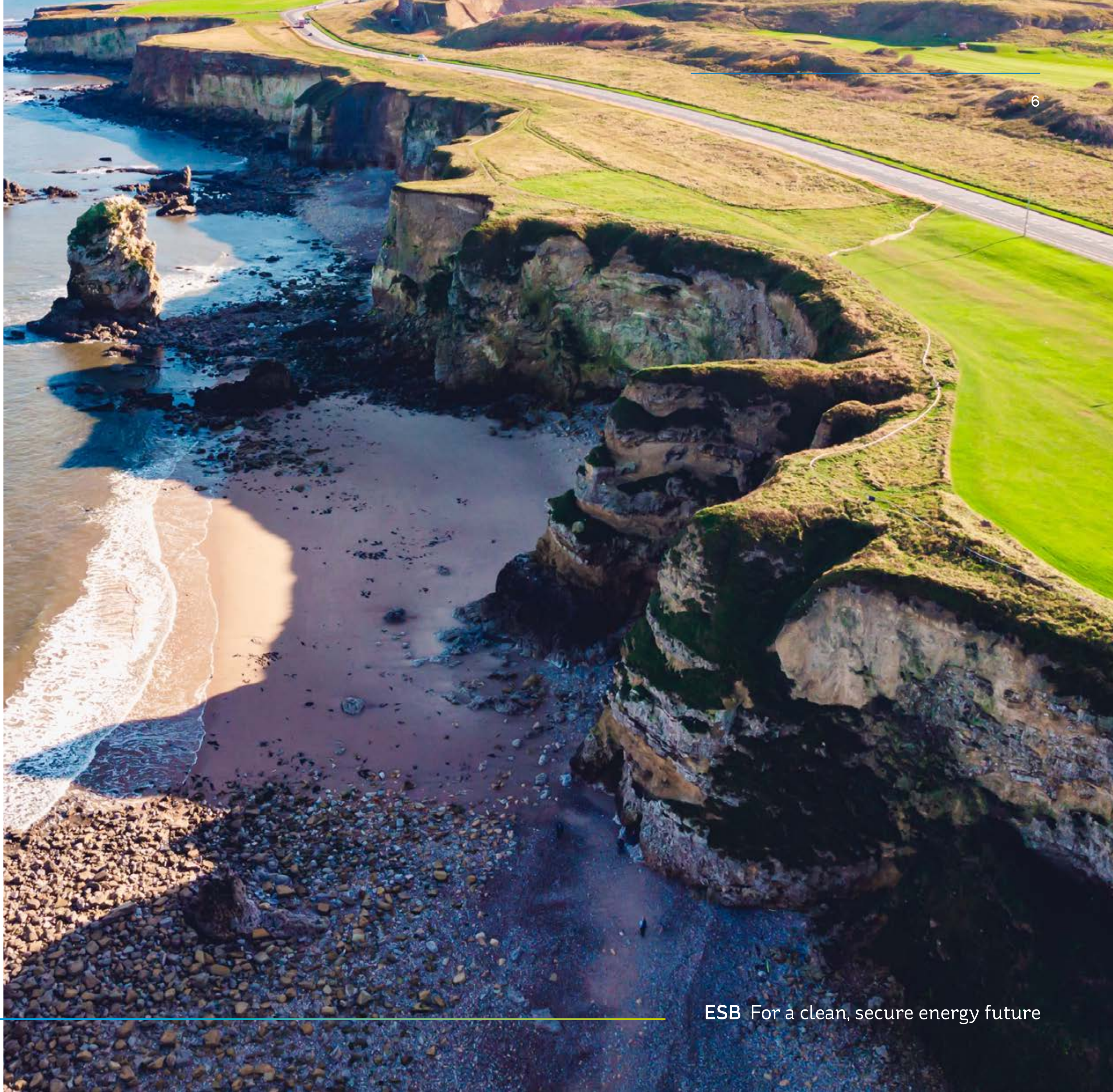
The future energy system will see widespread customer adoption of low-carbon heating technologies such as heat pumps and district heating. Improving the heating efficiency of existing buildings will be essential for this to succeed, along with expanded financial support to enhance understanding and adoption of these technologies by customers.

Ireland's energy system in 2050: Defining net zero

What does 'net zero' mean?
Net zero is defined by the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) as the state where "a balance between anthropogenic greenhouse gas emissions (emissions associated with human activities) and removals is achieved." This can be accomplished by ambitiously reducing and avoiding emissions in the first instance, and then implementing verified solutions to remove carbon equivalent to residual emissions.

Net zero in the energy sector means eliminating greenhouse gas emissions entirely or offsetting any residual emissions, while maintaining a reliable, affordable power supply, through:

- Reducing carbon emissions from electricity generation to zero or as close to zero as practicable
- Reducing fossil fuel consumption in heating and transport to drive direct emissions towards zero
- Using other energy sources such as bioenergy or e-fuels in hard-to-abate sectors, such as high temperature heat applications
- Dealing with any remaining residual emissions using a credible offset mechanism, carbon capture and storage (CCS) or negative emissions technologies



Whole energy system

Taking a big-picture view, our modelling shows that it is possible for Ireland to deliver a resilient, secure and highly electrified energy system powered primarily by home-grown renewables, enabling far greater energy independence than in the current fossil-based system.

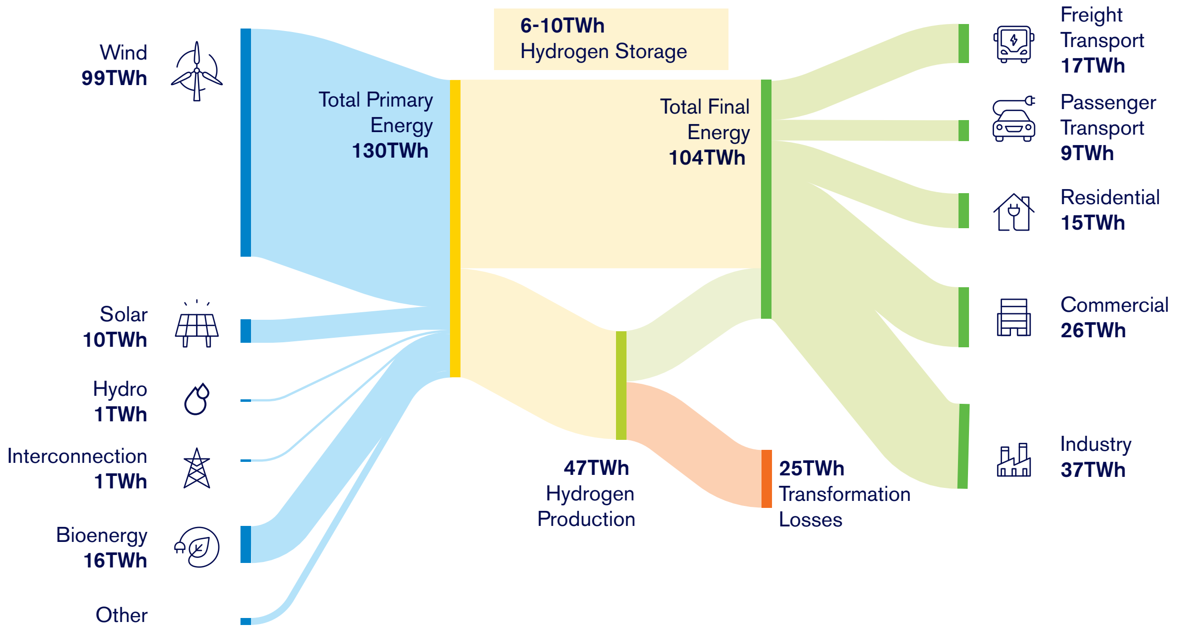
The figure opposite shows the overview of energy inputs (left) and outputs (right) for a 2050 energy system.

MaREI modelling was completed using the TIM Model – detailed model documentation is available here. Hydrogen storage modelling was completed by ESB and complimented by MaREI modelling.

A number of key insights stand out:

- The majority of primary energy – 84% – can be produced from indigenous renewables, complemented by interconnection and storage.
- Over 70% of our final energy needs in 2050 can be met directly by electricity, up from 22% in 2019. This assumes there will be widespread electrification of transport and heating, along with greatly increased uptake of electricity for industrial applications (this is addressed in more detail in subsequent chapters).
- More than 10% of final energy demand can be met indirectly by electricity through the production and use of hydrogen. When made using renewable energy like wind or solar, this energy source is carbon-neutral.
- The remainder of energy demand will be met by other sources such as bioenergy – energy that comes from organic matter such as plants and other natural materials, which can be used for electricity, heating and cooling, and transport.

Ireland's energy system in 2050



Negative emissions technologies will also be required to remove 3Mt CO2eq/yr in 2050, arising from process emissions and fossil fuel emissions in niche applications, due in part to timing of investment decisions in the UCC model.

~2.5x
increase in electricity demand in 2050 compared to 2019

>70%
proportion of final energy demand met by electricity

~80%
proportion of transport, residential and commercial energy demand met by electricity

Whole energy system: Carbon removal options

Even with significant renewable power, energy efficiency and electrification by 2050, Ireland will still have some residual greenhouse gas emissions from its energy system in niche areas where fossil-fuel use cannot be avoided, and in process emissions from cement production and emissions from waste.

These residual emissions represent the last kilometre of decarbonisation. To achieve net zero, carbon capture and negative emissions technologies will be needed to take this carbon dioxide from the atmosphere and store it.

Research and development work is ongoing on a number of carbon capture solutions, including:

Bioenergy carbon capture and storage (BECCS)

This involves burning renewable biomass and capturing its carbon dioxide, resulting in a negative carbon balance.

Direct air carbon capture (DACC)

This technology uses large-scale fans to push air through a filter capturing the carbon.

Nature-based solutions

Research is ongoing into nature-based carbon capture solutions involving use of land and the oceans – these include afforestation and reforestation, biochar soil carbon, or ocean fertilisation.

There is still a degree of uncertainty over both the quantity of residual emissions that will need to be addressed, and the most effective technology to remove them. Deploying carbon capture involves substantial investment, extensive infrastructure development, and the establishment of a regulatory framework. State guidance will be needed to determine whether solutions should be domestic or international.

By 2050, our average yearly electricity needs will be 2.5 times greater than today, requiring an 8-fold increase in renewable capacity - with backup generation needed for times of low renewable output.

Electricity system: Renewable generation

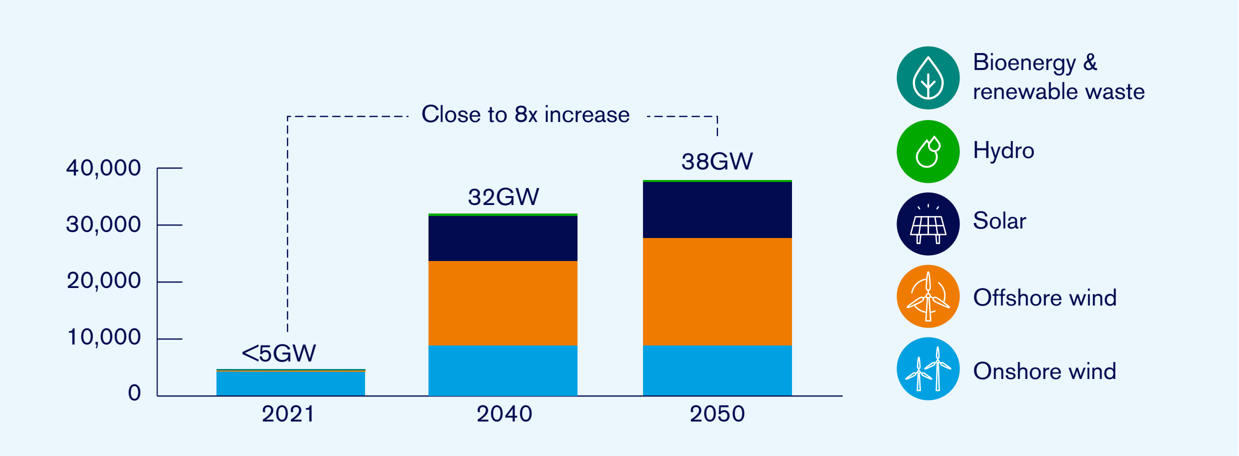
Ireland can achieve a zero-carbon electricity system by 2040, as a foundation for delivering net zero across the wider energy system by 2050. On the one hand, this will require a massive buildout of renewable energy generation: on- and offshore wind, and solar power. On the other hand, the system will need solutions for backup generation and electricity storage for times when the wind is not blowing and the sun is not shining.

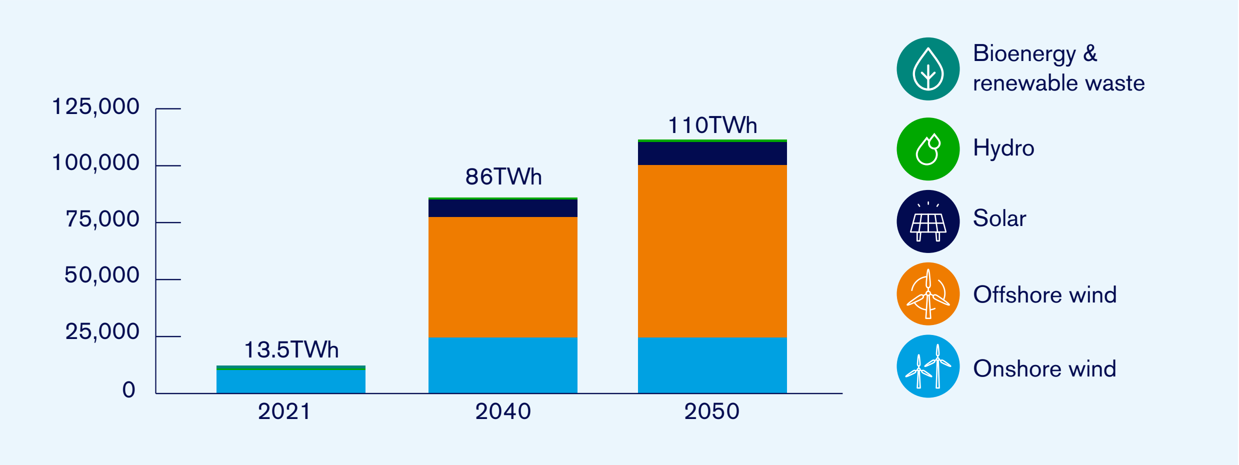
Renewables
Renewable energy will be the backbone of Ireland's future electricity system. Building new renewables is a national priority, and is intrinsically linked to securing Ireland's energy future by reducing reliance on imported carbon-intensive fuels.

By 2050, our average yearly electricity needs will be 2.5 times greater than they are today. This means that we will need an eight-fold increase on current renewable capacity to meet this increased electricity demand.

The majority of this capacity will come in the form of onshore and offshore wind, with an important role also to be played by solar energy. Solar power has rapidly advanced in recent years as a valuable complement to wind, and is projected to fuel much of renewable growth in the years ahead.

Between now and 2030, it is expected that growth in renewable energy will primarily be driven by new solar and onshore wind. After 2030, offshore wind is expected to surpass solar and onshore as the main source of renewable electricity.





Electricity system: Backup generation and storage

In a future electricity system where renewables are the primary power source, backup technologies will be needed during periods when wind and solar generation cannot meet demand.

There are several options available to provide this backup within a net zero system, with some better suited to Ireland's requirements than others:

Zero-/low-carbon fuelled dispatchable generation

This flexible resource can be ramped up and down in response to changes in demand, complementing the expected very high levels of wind and solar. This would include open- or combined-cycle gas turbines powered by low- or zero-carbon fuel that could be produced and stored in Ireland.

Large-scale interconnection

Interconnection between Ireland and neighbouring countries is a critical part of the electricity system, and large capacities are envisaged in the future. However, as periods of low wind in Ireland may coincide with similar weather across interconnected regions in Northern Europe, local dispatchable capacity will still be needed.

Large-scale electricity storage

Short-duration battery storage (2-4 hours) is a mature technology already widely used to provide important system services. While promising technologies are emerging for longer-term battery storage, this may not be feasible at volumes needed to store more than ten days of electricity demand for example.

Natural gas/coal/biomass with carbon capture and storage (CCS)

While CCS could play a role in future, it does not capture 100% of emitted carbon dioxide. It would also lock Ireland in a continued reliance on fossil fuels or imported bioenergy.

Nuclear electricity

Nuclear power offers several potential benefits for electricity systems and can help reduce long-term energy storage requirements. However, it cannot fully replace the need for long-duration storage and faces a unique set of development challenges in the Irish context.

Zero-/low-carbon dispatchable generation is seen as particularly crucial for a secure net zero electricity system in Ireland, in combination with large-scale interconnection and electricity storage.

Electricity system: Net zero versus near zero

The core net zero model

To achieve net zero emissions and maintain reliable power supply, it will be necessary to have enough low-carbon fuel stored so that dispatchable generators can run the system for over two weeks if needed.

Our modelling has demonstrated the potential benefits of using renewable energy to generate hydrogen in an optimised system, which would result in a zero-carbon fuel. On this basis, the modelling has produced a 'core net zero model' that assumes the following volumes of generation:

- **9 GW** Onshore wind
- **11 GW** Hydrogen gas turbines
- **17 GW** Offshore wind
- **10 GW** Solar
- **3 GW** Interconnection
- **2.7 GW** Batteries (12-hour)

Alternative scenarios

Using hydrogen to generate electricity is an emerging technology, and while there is a great deal of research underway to tap into its potential, domestic production will not be available in the required timeframe.

Our modelling therefore also considered alternative scenarios without hydrogen generation and storage, where unabated natural gas was the residual dispatchable generation source. These include an alternative model with no hydrogen, and a number of scenarios without hydrogen but with use of mitigating technologies (24-hour battery storage, interconnection, or zero-carbon peakers – turbines designed to run for short durations during peak demand, using zero-carbon fuels like biofuels or e-fuels).

The table on the right demonstrates how carbon emissions would vary between the core model (with hydrogen) and an alternative model (no hydrogen) with the use of these mitigating technologies.

Core model vs alternative scenarios

Model/mitigating technologies	Emissions in 2050[1,2]
The core model	0Mt
Alternative model - no hydrogen	1.4Mt
(1) Extra battery storage (5GW of 24h)	0.9Mt
(2) Extra interconnection (5GW)	1.3Mt
(3) 1GW zero-carbon peakers (1,000h per annum)	1.4Mt
Combination of (1), (2) and (3)	1.0Mt

[1] The emissions above refer to an average renewables production year. In a year of very low wind output, all but the core scenario would see emissions approaching 4Mt.

[2] Emission numbers were adjusted by ESB to reflect a 40% plant efficiency, instead of the 50% efficiency used in the UCC model.

While long-duration batteries offer most potential to reduce emissions in the absence of hydrogen, more interconnection and zero-carbon peakers can reduce carbon further but also impact on cross-border flows which affects emissions.

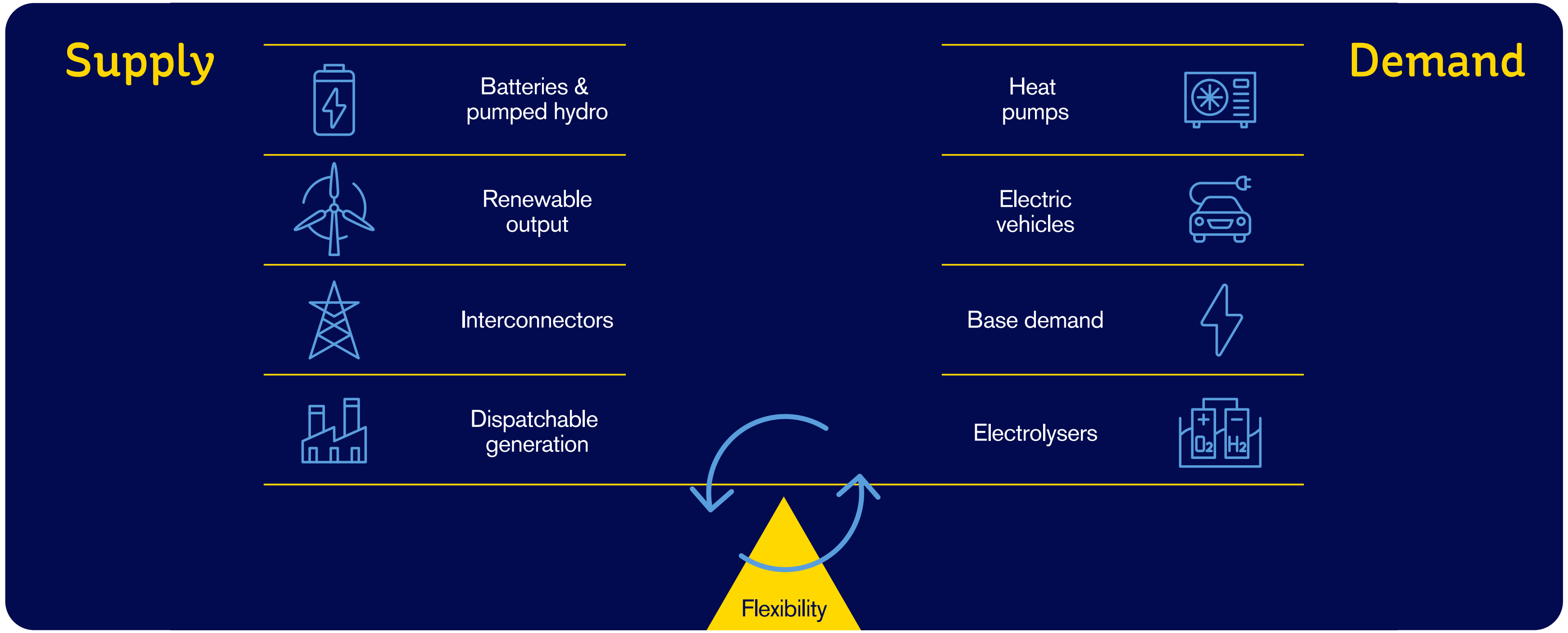
It can therefore be concluded that without hydrogen, a zero-carbon system resilient to prolonged periods of low wind/solar is unlikely to be possible.

As we transition to a net zero energy system where renewables are the main power source, we will have to think about our electricity system in a new way – with a greater focus on three key elements: flexibility, resilience and security of supply.

Flexibility, resilience and security of supply

Flexibility
The zero-carbon electricity system will be powered primarily by wind and solar, and while these variable energy sources sometimes generate less than needed to meet demand, they often generate far more power than can currently be absorbed. For this reason, flexibility and flexible demand in particular will play a crucial role in this future system.

Smart technologies and shifts in consumer behaviour will enable electricity demand to behave differently than it does today. For example, electric vehicles can be charged at times of high wind, and heat pumps operate in ways that maximise the use of renewable electricity. Excess renewable energy can feed into batteries in our homes and cars and at utility scale for short-term storage, and can power pumped hydro generation.



Resilience
With over 70% of final energy demand to be met by electricity in 2050, Ireland's future electricity system will need to be highly resilient to minimise outages. This will require an enhanced focus across a range of areas including:

Climate change adaptation

As rising temperatures bring more volatile weather, electricity network infrastructure will need to be able to withstand more frequent extreme weather events.

Storm recovery

As the frequency and severity of storms increase, rapid response to storm damage will be vital – particularly as people rely increasingly on electricity to meet their energy needs.

Cybersecurity

Greater use of digital technology brings many opportunities for the network, but robust cybersecurity is essential to safeguard against cyber-attacks.

Post-fault restoration

With electricity delivering ever more of our energy needs, it will be important to restore faults rapidly when they do occur, including through greater use of automated systems.

Flexibility, resilience and security of supply

Security of supply
By 2050 most people will be entirely reliant on electricity for their energy needs. This means that the electricity system must be resilient and secure with disruptions of supply kept to an absolute minimum.

In a fossil fuel-based power system, it is comparatively straightforward to store energy over longer periods of time. This is because fossil fuels provide on-demand dispatchable power and their stored energy can be converted to electricity instantly. As we move to a zero-carbon electricity system, it will be essential to consider alternative ways to deliver a similar level of security of energy supply.

A range of measures and initiatives will be needed:

Ireland's electricity system will be predominantly renewables-based, with wind and solar at the core of national supply. A complementary mix of renewables will be important to support security of supply.

Supply-side flexibility services are important, including interconnection, batteries and other multi-hour to multi-day storage solutions to bridge to seasonal storage of electricity.

Significant dispatchable capacity will still be needed for times of low renewables output and limited interconnector imports. This generation will provide a critical role in ensuring security of supply to the electricity system, but it will run infrequently.

To ensure zero-carbon electricity supplies in times of prolonged low renewables output, Ireland will need between 6 and 10 TWh of large-scale seasonal hydrogen storage. In advance of hydrogen deployment, natural gas storage will be a key component of a secure electricity system.

Demand-side flexibility will be essential in a zero-carbon energy system to maximise use of renewable energy while minimising cost to the consumer.

The continued electrification of customers' everyday energy needs across heat, transport and industry will empower people and communities to shape a cleaner, brighter and more sustainable future.

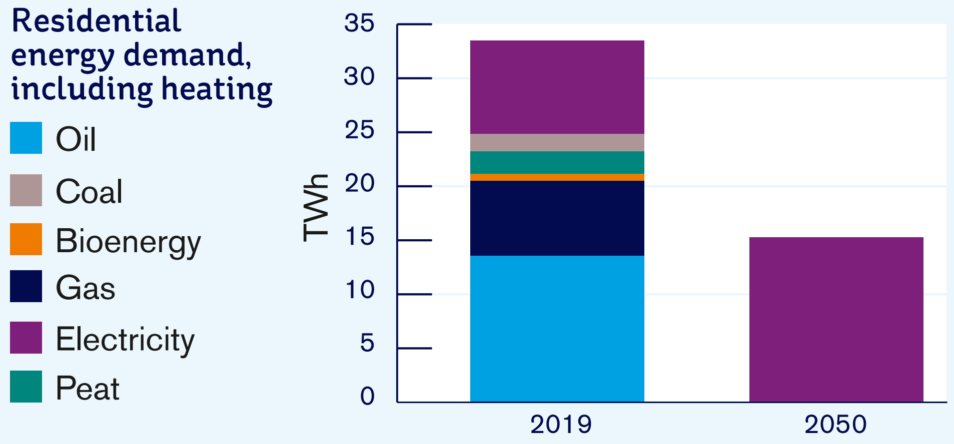
Heating

Today, the vast majority of homes and businesses are heated using fossil fuels. In the future net zero energy system, domestic and commercial heating requirements can be entirely met by electricity. Achieving this will require a combination of electric heat-pump deployment and improvements to energy efficiency.

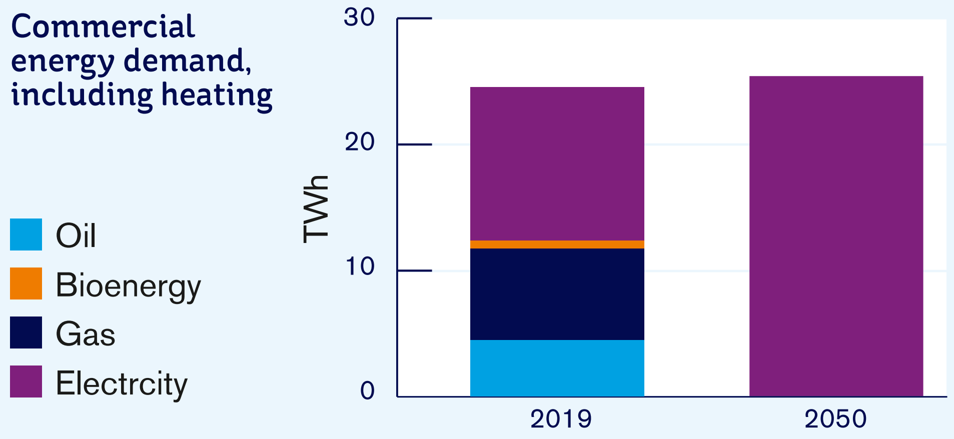
Low-carbon heating solutions
According to the International Energy Agency, the most important action households and businesses can take to accelerate the clean energy transition is to install a heat pump while implementing energy efficiency measures – something that is reflected in the Irish Government's policy for domestic and commercial heating.

- For new homes, electric heating is already standard in Ireland – over 90% of new builds are installed with electric systems today.
- For existing houses, an increasing number of heat pumps will be deployed in future; some of these homes are already heat-pump ready, while some will require retrofits.
- There is significant potential to use large scale heat pumps for district heating applications, whereby heat generated centrally is distributed to residential or commercial sites through piped heated water.
- For commercial buildings, it is expected that increasing numbers of heat pumps will be installed in new builds or as part of a retrofit.

Improved energy efficiency
To maximise the performance of electric heating systems, building fabric will need to be improved through energy efficiency measures like insulation and air sealing. For new builds, this is ensured through building regulations that are designed to progressively eliminate fossil heating technologies. For older buildings with poor energy performance, retrofits will deliver immense reductions in heating loads, making heat pumps a practical and affordable solution.



The model assumes an increase in the number of total dwellings between 2019 and 2050; however overall energy demand is expected to markedly decrease due to the efficiency gains of using electric-powered heat pumps over gas or oil.

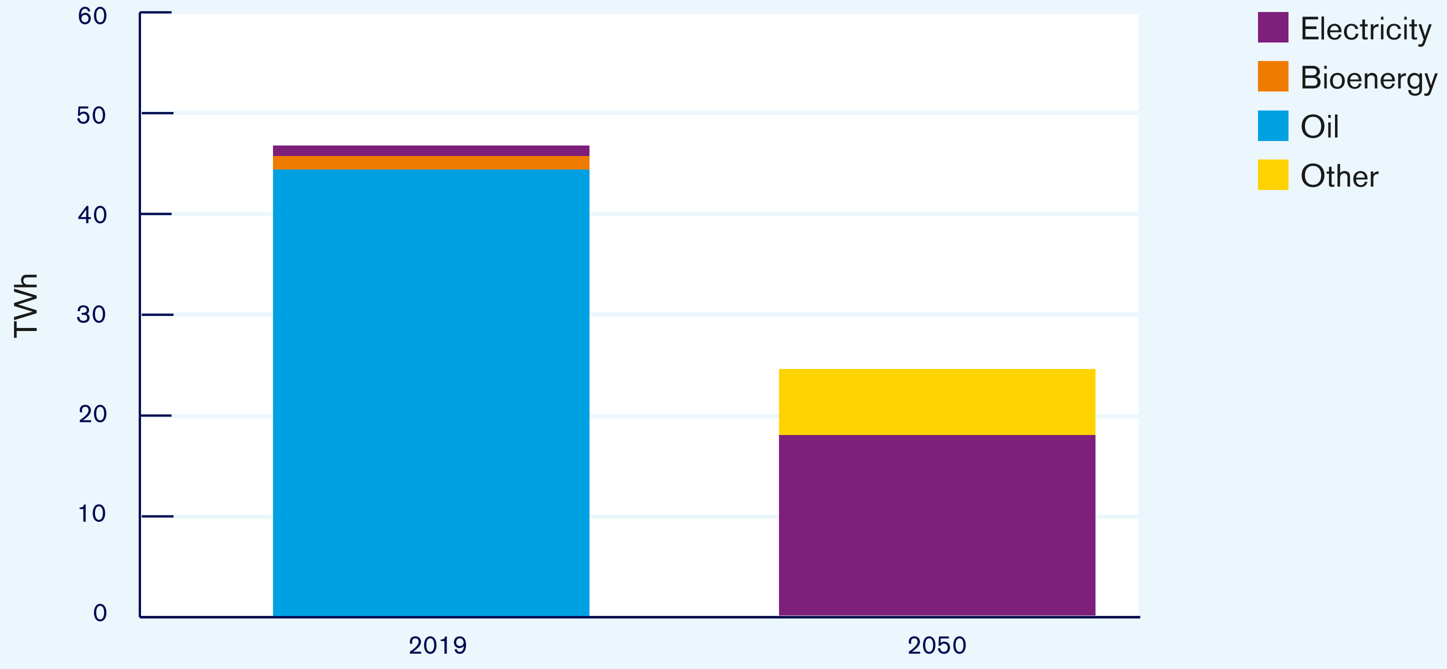


Transport

Today, transport accounts for around 20% of Ireland's total greenhouse gas emissions, mainly from petrol and diesel road vehicles.* By 2050, electricity will power most transport energy needs. Decarbonisation of the sector will be driven by this electrification, coupled with other trends including:

- In addition to a widespread move to electric vehicles, decarbonisation will be further driven by a modal shift to active travel, public transport and rail freight. While population growth will lead to a greater number of vehicles in circulation, particularly for freight, this increase will be tempered by that broader modal shift.
- Efficiency gains from electric vehicles along with the modal shift to other transport forms will result in a reduction in the overall transport energy requirements in 2050.
- All but the heaviest and more niche vehicles will be electrified; for those where electrification is not possible, biofuels/e-fuels can play a role. Hydrogen derivatives may have a role in hard-to-abate applications such as international marine and aviation. The 'Other' category in the figure presented here refers to electricity and biofuels/e-fuels, with the proportions of each depending on ultimate technology adoption.

Transport energy demand (road, rail, air* and maritime)

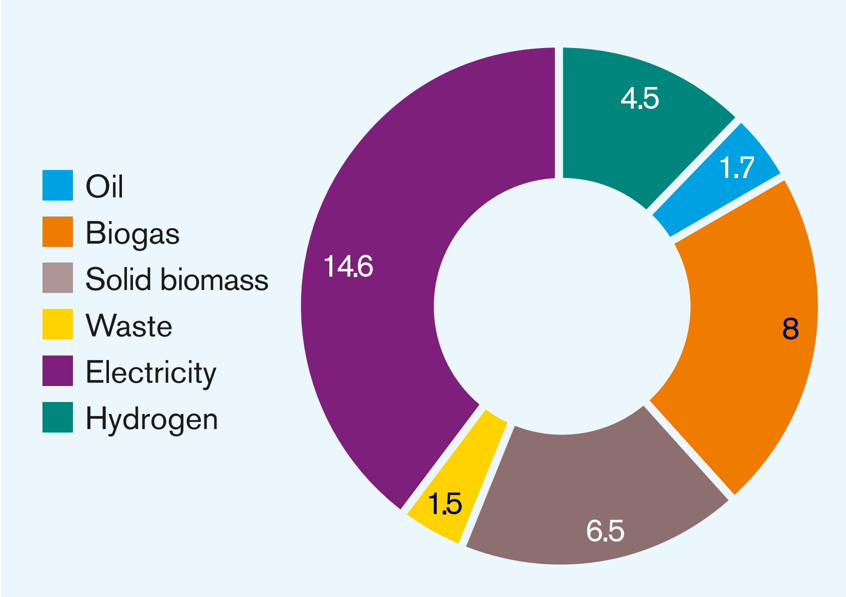


** Modelling excludes international aviation emissions.*

Industry

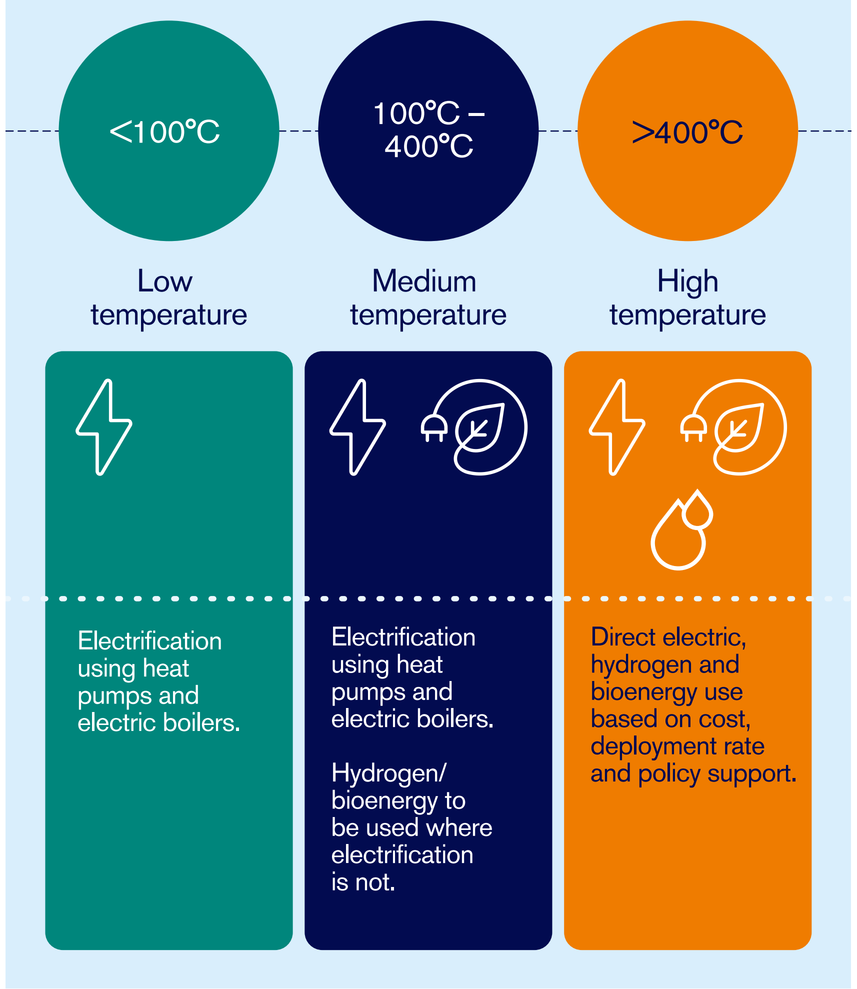
The high volumes of energy needed for industrial applications make decarbonisation in industry a significant challenge; however, it can be achieved through a range of technologies and fuels, with electricity playing a major role.

2050 Industry energy requirement (TWh)



Given the impact that high, volatile fossil fuel prices have had on competitiveness in recent years, decarbonising Ireland's industrial sector will be key to maintain and increase economic activity in the sector – while providing high quality jobs in the transition. The Government's Roadmap for Decarbonisation of Industrial Heat provides a blueprint for the sector with next steps on implementation being key.

- Electrification will feature prominently as temperatures achievable with heat pumps exceed 200°C and technologies such as electric boilers are further deployed. This is likely to be used in conjunction with behind-the-meter generation and storage.
- For very high temperature applications, hydrogen, biogas, and biomass could feature as energy sources. Bioenergy solutions, including resources supported under the Government's Biomethane Strategy, will ultimately be directed to high temperature heat. Bioenergy could be subject to resource and sustainability constraints, however, which would limit its availability.
- Ireland will need to deploy negative emissions technologies to capture carbon from industrial processes.
- The final share of each technology will depend on policy decisions, deployment rates, and cost.



A zero-carbon energy system in Ireland by 2050 is possible - but sustained rapid progress on all fronts is needed to make it happen.

A clean, secure energy future: How we get there

As the modelling carried out for this paper has shown, a zero-carbon energy system in Ireland by 2050 is possible. However, sustained rapid progress is needed on all fronts to make it happen.

Whole energy system

- Customers must be empowered and supported in the transition through initiatives such as awareness campaigns and financial supports for adoption of low-carbon technologies and energy efficiency measures.
- An Energy System Masterplan addressing energy use across electricity, heat and transport is needed, to work alongside Ireland's climate framework. By modelling the whole-of-energy-system scenario, a cross-government long-term energy plan would include a sector-by-sector analysis of energy use, identifying optimum technology for deployment and long-term strategy for same.
- A robust planning system will be essential to give certainty to all stakeholders and support efficient delivery of renewables projects.
- The transition to a net zero energy system will present many new opportunities, and Ireland will need a workforce with the right skills to benefit from the jobs which will be created by new projects and initiatives.

Electricity system

- Scaling up renewable generation is critical for Ireland's secure energy future. Building new wind and solar capacity is a national priority, and must be accompanied by new system operation practices and new system services.
- The electricity grid is key to decarbonising Ireland's energy use and requires significant investment to meet increasing demand from electrification and economic activity.
- Electricity market design is an important enabler in delivering net zero. The market design must support a secure electricity system with increased levels of renewable penetration, increased customer electrification and greater flexibility and demand side participation.

Flexibility, resilience and security of supply

- Customer-led demand-side response and demand flexibility will be key in a low-carbon electricity system. Smart meters will unlock customer participation in initiatives such as aggregation and flexibility markets.
- To support backup generation, green hydrogen production and storage is an optimal low-regrets option for Ireland that best fits with our high renewables ambitions.
- Bioenergy will play a small but important role in decarbonisation, making it important to deliver supplies of biomethane to the market soon.

Heating

- Supporting customers to complete energy efficiency measures and to move from fossil to electric heating is critical. Expanded financial support will be needed to encourage greater understanding and adoption of low-carbon heating technologies such as heat pumps and district heating, as well as measures to improve the heating efficiency of existing buildings.

Transport

- A societal transition to low-carbon alternatives such as electric vehicles, public transport, and active travel will require significant investment and planning in innovation and infrastructure – including a comprehensive charging network for electric vehicles – along with a supportive policy framework.

Industry

- Low-carbon industrial processes and technologies will need to be enabled through the formulation of support schemes, policies and regulations to encourage the use of low-carbon technologies such as carbon capture and storage.

Energy for generations

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For a clean, secure energy future:
Ireland's pathway to a net zero energy system by 2050
January 2026