



Energy for
generations

Emerging Technology Insights 2026

ESB Innovation



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Executive Summary

ESB’s strategy, Driven to Make a Difference: Net Zero by 2040, commits ESB to delivering a resilient, affordable and decarbonised energy system. Established technologies, such as onshore and offshore wind, solar photovoltaics and lithium-ion batteries, are already being deployed in Ireland at scale and will remain central to achieving a net zero energy system. However, additional technologies will also be needed to achieve that ambition. This report identifies emerging technologies that may be of strategic relevance to ESB and Ireland as the energy system transitions towards net zero.

This report reviews leading emerging technologies across the following six strategic categories:

No single technology will deliver Ireland’s net zero electricity system. The transition will require a broad portfolio of solutions spanning low-carbon generation, long-duration energy storage, customer flexibility, carbon management, grid resilience and electrification.

The overall picture is one of accelerating innovation, rapid technology development and increasing electrification. Some nascent technologies are already entering commercial deployment, while others remain at demonstration or early pilot stage. ESB will monitor fast-moving developments, pursue targeted trials where there is strategic relevance, and build partnerships that can help convert emerging technologies into affordable, deployable solutions for Ireland’s net zero electricity system.



Low Carbon Generation

Advanced generation technologies, including floating offshore wind, ocean energy, next generation geothermal, renewable hydrogen and ammonia, advanced solar technologies, small modular reactors and nuclear fusion could expand Ireland’s renewable and low-carbon resource base and provide new sources of firm or flexible low-carbon generation.

 Wave Energy (Pg 16)



Energy Storage

Long-duration storage technologies and renewable fuels, including sodium-ion, flow, CO₂, liquid air, thermal and iron-air storage, alongside hydrogen storage, bio-derived fuels and e-fuels, have the potential to help store excess renewable electricity, shift energy across hours, days and seasons, and support future system resilience.

 Thermal Energy Storage (Pg 32)



The Empowered Customer

Technologies such as vehicle-to-everything charging, smart charging, balcony solar, flexible and floating data centres, anaerobic digestion and biomethane may enable customers, businesses and communities to generate, shift, reduce or export energy in ways that support the wider system.

 Anaerobic Digestion and Biomethane (Pg 45)



Carbon Capture, Utilisation and Storage Technologies

Bioenergy with carbon capture and storage, point source carbon capture and direct air capture can help manage residual emissions, support carbon removals and create future carbon management value chains.

 Point Source Carbon Capture (Pg 48)



Grid Technologies

Technologies such as grid forming inverters, dynamic line rating, high temperature superconducting cables, SF₆ free equipment and medium-voltage direct current could increase system stability, capacity and resilience as renewable penetration rises.

 High Temperature Superconductor Cables (Pg 54)



The Electrification of (Almost) Everything

Technologies such as battery electric heavy goods vehicles, electric rail, improved EV charging, electric flight, electric shipping, reversible heat pumps, industrial heat pumps and novel forms of district heating will accelerate fossil fuel displacement across transport, heat, buildings and industry.

 Electrification of Shipping (Pg 66)



Overview

Purpose

This report reviews emerging energy technologies of relevance to ESB and the wider Irish energy transition. It provides an update on technology progress, market developments and relevant ESB activities. In doing so, it aims to support informed discussion, collaboration and innovation.

Scope

This report is not an exhaustive review of all emerging energy technologies. Instead, it focuses on selected technologies that could help address key challenges in Ireland's energy transition, including affordability, low-carbon generation, system resilience, customer participation and residual emissions management.

The report focuses on technologies that are not yet fully mature or widely commercialised but could have strategic relevance for Ireland. Mature technologies such as onshore wind and Li-ion batteries are excluded, except where they provide useful context for comparison.

Technologies are assessed primarily against five criteria: Technology Readiness Level (TRL), expected time to commercialisation, potential to scale, cost outlook and relevance to ESB.

Commercialisation

Commercial readiness, expected deployment timelines and indicative costs are assessed for the Irish, UK and relevant international markets where possible. Cost figures are based on publicly available sources and should be treated as illustrative rather than definitive.

How to read this report

Each technology section follows a consistent structure covering sample projects, cost, timelines, potential to scale, ESB activity, leading organisations and summary outlook. This allows technologies across different categories to be compared on a broadly consistent basis.

Looking ahead

As ESB approaches its 100th anniversary in 2027, the pace of change across the energy system has never been greater. Meeting Ireland's decarbonisation goals will require ambition, collaboration and a willingness to explore a wide range of technologies, from those already moving towards commercial scale to those still at an early stage of development. ESB is increasing its focus on innovation so that it can identify, test and deploy the solutions that will help deliver Ireland's transition to a net zero energy system.

We hope this report gives readers a clear sense of the speed of progress, the breadth of technologies being developed and the opportunities ahead. Most importantly, we hope it encourages further discussion on how ESB and its partners can help deliver an affordable, resilient and net zero energy future for Ireland.



Contact us

ESB recognises that it cannot deliver the energy transition alone. We welcome engagement from researchers, start-ups, technology providers, developers, customers and other partners. If you have an idea, project or insight that could help advance emerging energy technologies or support Ireland's transition to net zero, please contact ESB at innovation@esb.ie. While we may not be able to respond to every email, we will read and consider all submissions.

ESB Innovation 2026 Highlights

In 2026, ESB:



Trialled hydrogen power generation at a data centre



Tested HVO in two of its power stations



Began construction of its first hydrogen electrolyser



Began dynamic line rating trials on overhead lines



Continued to develop large-scale subsea hydrogen storage



Started installing a direct air capture trial at Aghada Power Station



Applied for EU funding for a pilot e-fuel production project



Procured its first non-SF₆ MV GIS boards and Circuit Breakers

Significant progress continues to be made across a range of emerging technologies covered in this report. Key recent milestones include:



The 16.8 MW Goto Floating Offshore Wind Farm in Japan began commercial operations.



CorPower Ocean received the world's first DNV Prototype Certificate for its full-scale wave energy converter, while Seaturms deployed a full-scale wave energy demonstrator off the French Atlantic coast.



ESB deployed its hydrogen fuel cell technology at multiple locations, including a data centre, and broke ground on its first electrolyser project.



Alfen and CATL signed a 5 GWh sodium-ion battery storage agreement for Europe.



BYD deployed a 1 MW flash charger in Paris, France, capable of adding up to 400 km of EV range in five minutes.



France confirmed a 250 MW tidal stream allocation in its 2026 energy roadmap, to support the industrialisation of tidal energy by 2030.



Geothermal Engineering's United Downs project in Cornwall began producing continuous geothermal electricity.



A 130 m fully electric ferry that can carry 2,100 passengers and 225 vehicles was built in Australia.



Heart Aerospace operated a fully electric regional scale aircraft for almost 30 minutes.



EPRI's DCFlex initiative expanded to nine demonstration projects testing data centre demand flexibility.



China's LingLong 1 Small Modular Reactor began commissioning activities in 2026.



LONGi set a certified world record of 35.5% for silicon-perovskite tandem solar cell efficiency.

These milestones show that several emerging technologies are moving from demonstration towards early commercial deployment, while others are attracting the investment and policy support needed to scale.

Technology Radar

The Technology Radar provides a comparative view of the maturity and outlook of the technologies reviewed in this report. It is intended to support prioritisation by showing where technologies sit today and how quickly they may become relevant to Ireland. Each technology has been assigned a single illustrative TRL for comparison purposes.

TRL 1-2 Concept phase / research

TRL 3-5 Small scale prototype deployed in lab / controlled environment

TRL 6-7 Large scale prototype or subsystems deployed in controlled environment

TRL 8 Large scale prototype deployed in commercial type environment

TRL 9 Mature technology, deployed at scale in commercial type environment

More than 10 years to Commerciality

1-5 years to Commerciality

5-10 years to Commerciality

Commercial / Early Commercialisation

TRL progress over the last year

Commerciality timelines are subjective, indicative estimates of when each technology could be commercially deployed in Ireland.



Artificial Intelligence

Artificial intelligence is one of the most influential technologies of our time. It is rapidly becoming embedded across both society and the workplace, often in ways that are seamless and largely invisible to users. In daily life, AI supports activities such as searching for information, comparing products and services, navigating digital platforms and personalising online experiences. It is also transforming how organisations operate, deliver value and engage with customers, from enhancing customer experiences and digital services to supporting employees with analysis, planning, reporting and decision-making.

Within ESB, AI tools are increasingly available to employees and are helping to support the design, construction and operation of a modern electricity system. AI can support renewable generation forecasting, network planning, asset management, predictive maintenance, customer engagement and engineering design. It can also assist in document-heavy processes such as consenting and project development. Used well, these applications can help accelerate low-carbon generation, improve network resilience, support customers and contribute to ESB's ambition to deliver a net zero electricity system by 2040.

AI is not treated as a separate emerging technology in this report because it is already embedded, implicitly or explicitly, across almost every technology area considered. Suppliers, developers, researchers, technologists and integrators are using AI to improve products, optimise processes and generate insights from complex data. When appropriately governed and applied, AI can support decarbonisation by speeding up renewable development, improving decision making and generating data driven insights.

However, AI can also create new risks for electricity infrastructure and decarbonisation. It may improve public participation in planning and consultation processes, but it could also be used to amplify misleading information, increase the volume of submissions and undermine trust in development processes. Governance, cybersecurity, transparency and public confidence will therefore be important as AI becomes more widely used.

AI is also powered by electricity. Ireland's existing data centre load is largely associated with cloud computing, enterprise services and data storage. However, future growth in AI training and application could significantly increase demand for low-carbon electricity and grid infrastructure. This reinforces the importance of planning AI and data related electricity demand in ways that support, rather than constrain, the transition to a net zero power system.

AI is likely to have a profound impact on Ireland's future electricity system, primarily through the way it shapes how other technologies are developed, deployed and operated. The challenge for governments, system operators, utilities and technology users will be to ensure that AI is managed and applied in ways that support and accelerate decarbonisation, protect public trust and improve outcomes for society.



Examples of the use of AI in ESB

AI is already being applied across the generation and trading business to improve operational performance and decision-making. In wind operations, machine learning and predictive models are helping to minimise turbine downtime by identifying potential faults before they occur. Hydroelectric power stations are using weather sensors and forecasting models to better predict output, while energy traders are applying AI to identify optimal times for battery charging and discharging based on market conditions and system needs. Together, these examples illustrate how AI can support asset optimisation, improve forecasting accuracy and enhance commercial decision-making.



1 | Low Carbon Generation

ESB's 'Driven to Make a Difference: Net Zero by 2040' strategy will require continued deployment of established low-carbon technologies alongside targeted development of emerging solutions that can address the remaining gaps in the transition to an affordable and resilient high-renewables energy system. The generation technologies reviewed in the following section, including floating offshore wind, ocean energy, next generation geothermal, renewable hydrogen and ammonia, and advanced solar, are at different stages of maturity, but each has potential relevance to ESB's future low-carbon generation portfolio.

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1. Low Carbon Generation (continued)

TRL 9

Floating Offshore Wind



Dublin Offshore Technology's Load Reduction Device being installed in the Gulf of Maine in the US. The operation was part of a demonstration of the DeepCwind VoltturnUS+ concrete floating wind turbine foundation (Credit: Dublin Offshore Technology)

Floating offshore wind (FLOW) uses wind turbines mounted on floating foundations rather than fixed seabed structures. Mooring systems and anchors hold the platforms in place, enabling deployment in deeper waters where fixed-bottom offshore wind is unsuitable. Several floating platform concepts are under development, with the most mature moving into early commercial deployment. DNV has assigned TRL 9 to leading floating platform technologies.

Sample projects

Goto Floating Offshore Wind Farm, off the coast of Japan, is a 16.8 MW (8 × 2.1 MW turbines) project that started commercial operations in 2026. It is the world's first commercial deployment of a hybrid spar foundation (steel upper section, concrete lower section). Kincardine and Hywind Scotland are already operational in the UK, while Hywind Tampen in Norway supplies electricity to offshore oil and gas infrastructure. In France, Provence Grand Large was commissioned in 2025, adding another European reference project.

Cost

France has awarded two 250 MW Mediterranean floating projects at prices at or below €92.70/MWh, although these projects are located in more benign wave conditions than those typically found around Ireland. In 2026, France launched a large

offshore wind tender that included seven floating offshore wind projects. Recent auction outcomes suggest significant cost reductions may be possible as the sector scales. However, costs remain highly sensitive to project location, supply chain maturity, mooring and foundation design, and financing conditions.

Timelines

In Ireland, commercial-scale floating offshore wind is likely to remain on a 10+ year development horizon, reflecting the need for policy, consenting, grid, port and supply-chain development. Demonstrator and early commercial projects in Europe over the late 2020s and early 2030s will be important in reducing risks and improving deployment confidence.

Potential to scale

Floating offshore wind has significant long-term potential in Ireland, particularly off the south and west coasts where water depths and wind resources favour floating solutions. Estimates suggest at least 30 GW could be technically available, although the pace of development will depend on consenting, grid reinforcements, route-to-market design, and supply-chain and port readiness.

ESB Activity

ESB is developing a number of FLOW projects and advancing its understanding of the technology through its involvement in the following projects and activities:

- The 500 MW Stoura project off Shetland's east coast.
- An innovative 100 MW project called Malin Sea Wind.

- ESB, with EDF Renewables UK and Sumitomo Corporation, is co-developing the 1.5 GW Gwynt Glas Offshore Wind Farm, off the coasts of Devon and South Wales. Gwynt Glas was chosen as a preferred bidder in the seabed leasing round for floating wind projects in the Celtic Sea.
- ESB, with Northland Power, is jointly developing the 1.5 GW Havbredey project off the northwest coast of Scotland.
- In Ireland, ESB is progressing plans at Moneypoint to create a hub for floating wind projects. ESB is also awaiting updates from the Department of Climate, Energy and the Environment on plans for a floating demonstrator project.
- ESB has invested in Dublin Offshore Technology Limited, a developer of novel floating offshore wind mooring technology.

Leading Organisations

Leading floating platform developers include Principle Power for semi-submersible platforms and Equinor for spar-buoy concepts. Other active platform and project developers include BW Ideol, Hexicon, Saitec Offshore Technologies and SBM Offshore.

Summary

Floating offshore wind has a positive long-term outlook in Ireland because it could unlock large-scale renewable generation in deeper waters off the south and west coasts. The main challenges are cost, port readiness, grid connection, supply-chain capacity and operation in energetic oceanic conditions. Recent European pilot projects and auction activity show that the technology is progressing. However, Ireland will need clear policy, route-to-market and infrastructure development to convert its resource potential into commercial projects.

- TRL 1-2 Concept phase / research
- TRL 3-5 Small scale prototype deployed in lab / controlled environment
- TRL 6-7 Large scale prototype or subsystems deployed in controlled environment
- TRL 8 Large scale prototype deployed in commercial type environment
- TRL 9 Mature technology, deployed at scale in commercial type environment

TRL 4-5

Other Deepwater Fixed Offshore Wind Foundations



Deepwater foundations supporting offshore wind turbines (Credit: Marine Power Systems)

Other deepwater fixed offshore wind foundations are an emerging class of offshore wind support structures designed to operate in water depths beyond the practical limits of conventional monopile and jacket foundations currently used in the offshore wind industry. They seek to bridge the gap between traditional fixed-bottom offshore wind (typically up to water depths of 60-80 m) and floating offshore wind, which can operate in very deep waters.

The concept has gained attention following the UK government's introduction of the Other Deepwater Offshore Wind (ODOW) category within the AR8 support framework. This recognises that some innovative foundation concepts are designed for deepwater deployment but do not meet the formal definition of floating offshore wind. Other deepwater fixed offshore wind foundations are currently estimated at TRL 4–5 and remain pre-commercial. There has been no commercial-scale deployment of this technology to date.

Sample projects

Most concepts remain in the research and pre-commercial stage. Researchers are particularly interested in structures that eliminate the need for dynamic export cables and reduce floater motion, while retaining many of the advantages of fixed-bottom wind. The UK ODOW category provides a potential future route to market for these concepts.

Cost

No commercial benchmark exists. Potential benefits include elimination of mooring systems and dynamic cables and potentially lower operating costs. Challenges include very large steel or concrete requirements, specialised installation and high capital costs.

Timelines

The most likely pathway involves research and pilot projects before 2030 and first demonstrations in the early 2030s. Broader commercial deployment after 2035 is possible if the technology can compete with floating wind on cost and reliability.

Potential to scale

Ireland's Atlantic coastline features strong winds and deep water close to shore. Other deepwater fixed concepts could potentially offer greater stability and simpler electrical systems than floating wind. However, floating wind remains considerably more mature and is expected to dominate the first phase of Irish deepwater offshore development.

ESB Activity

ESB has assessed Ireland's offshore wind potential and is developing a number of floating offshore wind projects. ESB continues to monitor emerging foundation and mooring concepts to understand their potential relevance for future deepwater offshore wind development.

Leading Organisations

Potential leaders include Saipem, Technip Energies, MODEC and other companies with deepwater engineering expertise.

Summary

Other deepwater fixed foundations seek to combine the stability of fixed-bottom structures with the deepwater capability normally associated with floating wind. While still at an early stage, the technology could become relevant in deepwater markets such as Ireland if significant cost reductions and successful demonstrations are achieved.

1. Low Carbon Generation (continued)

TRL
6-7

Wave Energy



Seaturns wave energy converters undergoing sea trials off France's Atlantic coast (Credit: Christophe Beyssier & Seaturns)

Wave energy converters (WECs) capture the kinetic energy in ocean waves and convert it into electricity through power take-off systems. Designs vary, but most use the pitch, heave or surge motion of waves to drive mechanical, hydraulic or electrical systems. Wave energy remains at the demonstration stage. Leading technologies are typically assessed at TRL 6–7, although several full-scale prototypes are now being tested in real sea conditions.

Sample projects

Swedish company CorPower Ocean has deployed a full-scale prototype point absorber WEC off the coast of northern Portugal, successfully exporting power to the grid and surviving two major storms. It recently secured an EU Innovation Fund grant for a 15 MW array in the area. French company Seaturns completed a quarter-scale WEC demonstration project in 2025 and launched a full-scale demonstration in 2026, both off France's Atlantic coast. In 2026, it was also selected by the Mauritius Renewable Energy Agency for a 2 MW pilot farm connected to the grid, with a scale-up to 10 MW envisaged.

Cost

The UK Allocation Round 7, published in July 2025, set an administrative strike price for wave energy of £386/MWh in 2024 prices. To date, no wave project has been successful in UK allocation rounds. However, wave energy research is also benefitting from the data centre boom. Technology investor Peter Thiel, a co-founder of PayPal, invested US\$140 million in US WEC developer Panthalassa in 2026. The US company is developing an ocean-cooled, satellite-connected AI processing system powered by wave energy.

Timelines

Ireland's forthcoming *National Designated Maritime Area Plan for Offshore Renewable Energy* may help create a clearer pathway for innovative offshore technologies, including wave energy converters. Portugal has a national wave energy target of 200 MW of installed capacity by 2030. The EU Green Deal has set a target of 100 MW of ocean energy (wave and tidal) to be deployed by 2027 and 1 GW by 2030.

Potential to scale

Ireland has some of the best wave resources in the world, with the potential for up to 19 GW according to the EVOLVE research project. Significant further technology development, cost reductions, timely permitting and grid connections will be needed to achieve scale.

ESB Activity

ESB is collaborating with CorPower and Seaturns on their full-scale demonstration projects to monitor the key stages of the deployment and offshore trials, with access to technical data and live performance results under real operational conditions.

Leading Organisations

Leading wave energy organisations include CorPower Ocean, Seaturns, Eco Wave Power and Wave-Op. CorPower Ocean is one of the most advanced offshore wave energy developers, with a full-scale grid-connected device in Portugal and the first DNV prototype certification for a wave energy converter. Seaturns is progressing full-scale offshore testing and has been selected for a pilot project in Mauritius. Eco Wave Power is focused on shore-mounted systems, while Wave-Op is developing nearshore caisson-based technology in France.

Summary

Wave energy has experienced repeated setbacks over several decades, but recent full-scale demonstrations suggest that the sector is making progress. Technology developments led by companies such as CorPower Ocean are attracting public and private funding. The leading projects are addressing some of the fundamental challenges involved in commercialising wave energy, including storm survivability and structural efficiency. Overcoming these barriers will be critical to unlocking its potential. Ireland has a very strong wave resource, but wave energy remains less mature than offshore wind and tidal stream energy.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
8

Tidal Stream Energy



Tidal energy device harnessing power from ocean currents (Credit: Minesto)

Tidal stream energy converters harness the kinetic energy of horizontal tidal water flow to generate electricity. Three principal technology types exist: seabed mounted turbines, floating turbines and tidal kites. The International Renewable Energy Agency assesses leading tidal stream technologies at TRL 8.

Sample projects

In Scotland, Ampeak Energy's MeyGen project has operated four 1.5 MW turbines since 2018, with a further 59 MW planned for Phase 2. Orbital Marine Power's 2 MW O2 floating tidal turbine began grid-connected generation at the European Marine Energy Centre (EMEC) in 2021, and the company has secured Contracts for Difference support for additional projects in the UK and Canada. Magallanes Renovables has also tested its 1.5 MW ATIR floating tidal turbine at EMEC.

Elsewhere, Minesto's 1.2 MW tidal kite began grid-connected generation in the Faroe Islands in 2024, while Proteus Marine Renewables deployed its 1.1 MW AR1100 tidal turbine in Japan in 2025. In France, HydroQuest has tested seabed-mounted tidal turbines in Brittany and is progressing the 17 MW FloWatt project in Normandy with Qair.

Cost

In the UK's 2026 Allocation Round 7a, four tidal stream projects using different technologies - QED Naval/Tocado, Tidal Tech, Orbital Marine Power and Hydrowing - secured 20.9 MW of Contracts for Difference support at a strike price of £265/MWh (in 2024 prices). Although this remains high compared with mature renewables, tidal stream was the only Pot 2 technology to secure support in the round, indicating a clearer route to market than several other less-established technologies.

Timelines

Ireland's forthcoming *National Designated Maritime Area Plan for Offshore Renewable Energy* may help create a clearer pathway for innovative offshore technologies, such as tidal stream energy. In the UK, tidal stream is entering early commercial deployment, with around 140 MW awarded support contracts and an industry ambition of 1 GW by 2035. France confirmed a 250 MW tidal stream allocation in its 2026 energy roadmap, which supports the industrialisation of tidal energy. EU ocean energy targets covering both wave and tidal are 100 MW by 2027 and 1 GW by 2030.

Potential to scale

In the Republic of Ireland, tidal stream potential appears more limited than wave energy and offshore wind. Northern Ireland has a stronger tidal resource, with the potential for hundreds of MW of development, but no maritime planning

policy is in place. The UK and France each have the potential to achieve more than 1 GW of capacity before 2040 and multiple gigawatts after 2040. Outside Europe, Canada and Japan are important markets with high scaling potential.

ESB Activity

ESB is maintaining a watching brief on tidal stream energy.

Leading Organisations

Leading organisations include Magallanes Renovables and Orbital Marine Power (floating turbines), Ampeak Energy, HydroQuest and Proteus Marine Renewables (seabed mounted turbines) and Minesto (tidal kites).

Summary

Tidal stream energy is more mature than wave energy and is moving into early commercial deployment, supported by policy mechanisms in the UK and France. However, its outlook varies strongly by location. In the Republic of Ireland, utility-scale potential appears limited using current technologies, while Northern Ireland has stronger resource potential but an uncertain route to market. Great Britain and France offer clearer near-term opportunities because of stronger resources, defined support mechanisms and larger project pipelines.

1. Low Carbon Generation (continued)

TRL
7-8

Next Generation Geothermal Energy with Organic Rankine Cycle



GEL's 3MW United Downs EGS project in Cornwall showing the two wells, ORC heat exchangers, turbine and generator (Credit: Geothermal Engineering LTD)

Geothermal energy uses heat from within the Earth for heating, cooling or electricity generation. Geothermal may be broadly categorised as conventional or next generation, with the latter including Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS).

In conventional geothermal systems, fluids circulate through simple boreholes or naturally occurring fissures. However, in EGS, fluids circulate through engineered fissures. AGS are closed loop systems that act as large heat exchangers. Leading next generation geothermal technologies are at TRL 7-8, with EGS more established than AGS.

Organic Rankine Cycle (ORC) systems use a secondary working fluid with a lower boiling point than water to generate electricity from lower-temperature heat sources, enabling electricity generation from a lower temperature source and reducing turbine corrosion. The technology is at TRL 9 and has generally been used in smaller-scale power applications.

Sample projects

EGS: In July 2023, US-based Fervo Energy announced the successful full-scale test of its Nevada 3.5 MW test plant. Its Cape Station 100 MW Phase 1 project in Utah is under construction, with all wells drilled and first power produced in 2026.

EGS: In February 2026, Geothermal Engineering Ltd (GEL) started producing electricity from its Cornwall project in the UK, and Octopus Energy secured a long-term PPA for 3 MW from the project.

AGS: Canadian company Eavor is developing a project in Germany that will produce both heat and electricity. The project aims to deliver up to 64 MW of thermal energy and around 8 MW of electricity, with early loop testing demonstrating material heat output in 2026.

Cost

Geothermal costs are highly site-specific and depend on drilling depth, subsurface temperature, flow rate and geology. Next generation geothermal developers are seeking to reduce costs by applying techniques from the oil and gas sector and utilising advanced analytical tools. The Eavor AGS project in Germany will receive a fixed power price of €227/MWh until 2042 and a €92 million grant from the EU Innovation Fund. In the UK, the GEL project secured a 15-year Contract for Difference at £175/MWh (2026 indexed) for 2 MW of the United Downs project.

Timelines

Next generation geothermal is moving from demonstration towards early commercial deployment, particularly in the US and some European markets. Phase 2 of the Fervo Energy Utah project (400 MW) is planned for 2028.

Potential to scale

One attraction of next generation geothermal is that it could expand geothermal electricity generation beyond traditional volcanic or high-temperature geothermal regions. AGS, in particular, may be less dependent on natural permeability than conventional systems or EGS. If the technology progresses and the costs come down, next generation geothermal could become an important source of firm low-carbon energy.

ESB Activity

ESB is maintaining a watching brief on next generation geothermal.

Leading Organisations

Leading next generation geothermal developers include Fervo Energy, Geothermal Engineering Ltd, Eavor and Sage Geosystems. Leading ORC system suppliers include Turboden and Exergy International.

Summary

The global outlook for next generation geothermal is increasingly positive, with EGS and AGS projects moving from demonstration towards early commercial deployment. ORC technology is already mature and can support electricity generation from lower-temperature geothermal resources, but the main challenge remains the development of reliable, cost-effective subsurface heat extraction. For Ireland, the outlook for geothermal electricity is uncertain because available temperatures may be relatively low and subsurface data remains limited. However, the option warrants continued monitoring, particularly as drilling costs fall, project experience grows and better geological data becomes available.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
8-9

Hydrogen Production by Electrolysis



A photo of ESB's first electrolyser – it has been fabricated and will be installed in Aghada Power Station in 2027

Water electrolysis is a key technology for renewable hydrogen production. It uses electricity to split water into hydrogen and oxygen, and where the electricity is renewable, the hydrogen produced can also be considered renewable. Several electrolyser technologies are available, with alkaline electrolyser currently the most mature and widely deployed.

Proton exchange membrane (PEM) electrolyser are also commercially available. They can offer advantages such as a smaller footprint and more flexible operation, making them attractive for locations with space constraints or variable renewable electricity supply. Solid oxide electrolyser cells (SOECs) and anion exchange membrane (AEM) electrolyser are also being developed but they are at lower maturity levels. Each technology has different strengths and limitations, with the choice of technology depending on project-specific operational requirements.

According to the World Bank Group, alkaline and PEM electrolyser are at TRLs of 8-9, with approximately 1 GW of each technology installed worldwide in 2025. SOECs are typically assessed at TRL 6-8, while AEM electrolyser have reached approximately TRL 5-8, depending on configuration and supplier maturity.

Sample projects

In 2025, Envision commissioned a 500 MW alkaline electrolyser system at its renewable ammonia production facility in Chifeng, China. The facility, described as the world's largest renewable ammonia plant, is powered by a combination of wind turbines and batteries and operates fully off grid. Envision is also developing projects in Spain of similar scale.

Cost

Electrolyser costs depend on the supplier and technology selected. The World Bank Group reports installed cost ranges of approximately US\$500-1,500/kW for alkaline electrolyser, US\$1,000-2,000/kW for PEM, above US\$3,000/kW for SOEC and above US\$3,500/kW for AEM systems.

Timelines

Electrolysis-based hydrogen production grew strongly in 2025, with further growth expected in 2026. As electrolyser technologies mature and deployment increases, renewable hydrogen production is expected to continue expanding through the late 2020s, particularly where policy support and low-cost renewable electricity are available.

Potential to scale

The IEA expects global operational electrolysis capacity to exceed 7 GW by the end of 2026. It projects that capacity could exceed 440 GW by 2030 if all announced projects proceed, although their likelihood of delivery varies.

ESB Activity

ESB has broken ground on its first electrolyser project at Aghada, and it is expected to be operational in 2027. The 1 MW plant will produce hydrogen for ESB's existing hydrogen fuel cells, supporting practical demonstration of renewable hydrogen production and use.

Leading Organisations

Leading organisations include Plug Power, ITM, Thyssenkrupp Nucera, Cummins, LONGi Hydrogen and Sunfire.

Summary

Renewable hydrogen production through water electrolysis is reaching high levels of maturity, with several electrolyser technologies now available to meet different project requirements. Sustained growth in installed electrolysis capacity worldwide demonstrates that projects are increasing in scale, with individual developments now reaching around 500 MW. Downstream applications such as renewable ammonia and methanol production, alongside supply to existing industrial hydrogen users, are helping shift fossil-based hydrogen demand towards renewable electrolytic hydrogen. Continued global expansion of electrolysis capacity is expected, with China playing a major role in both renewable hydrogen production and electrolyser manufacturing.

1. Low Carbon Generation (continued)

TRL
7-9

Power Generation from Renewable Hydrogen



A photo of ESB's hydrogen fuel cell that converts hydrogen into electricity.

Hydrogen is a carbon-free energy carrier that can be generated via electrolysis from electricity and stored for conversion back to electricity. When produced using renewable electricity, hydrogen can be classified as renewable hydrogen and can be used as a low-carbon fuel for dispatchable generation.

Several technologies exist to convert hydrogen back to electricity, including gas turbines (TRL 7-9), reciprocating engines (TRL 9) and fuel cells (TRL 9). Gas turbines and reciprocating engines are widely used in the power generation industry, but their use with hydrogen is challenged by the characteristics of hydrogen combustion. Large-scale hydrogen power generation projects tend to blend hydrogen with natural gas to enable commercial deployment.

Sample projects

Mitsubishi has blended 30% hydrogen into a combined cycle gas turbine at Takasago Hydrogen Park in Japan, while General Electric has tested 100% hydrogen combustion in test turbines.

Cost

The cost of hydrogen-to-power depends on the cost of producing renewable hydrogen, storing and transporting it, and the technology used for power generation. In the UK, the average government-supported hydrogen production cost under the first Hydrogen Allocation Round was £241/MWh. The full cost of power generation from renewable hydrogen would be higher once storage, transport and conversion losses are included.

Timelines

In Ireland, utility-scale projects that combine renewable hydrogen production, storage, transport and 100% hydrogen combustion are most likely to emerge after 2035.

Potential to scale

Given Ireland's offshore wind ambition, renewable hydrogen has significant potential to scale and could enable the storage of terawatt-hours (TWh) of energy, providing a seasonal storage solution that would require the scale-up of hydrogen power generation technologies.

ESB Activity

ESB is actively pursuing the potential blending of hydrogen at its 886 MW Carrington power station in Manchester, UK. Technical studies have been completed by the original equipment manufacturer (OEM), Ansaldo Energia, and the project is awaiting a UK Government decision on progressing a hydrogen network in the region. ESB owns similar combined-cycle gas turbine technology in Ireland, which could potentially be adapted for hydrogen firing in future.

ESB has also demonstrated green hydrogen use through its Hydrogen Power Units, which produce electricity from hydrogen gas. It has collaborated with external partners to demonstrate hydrogen as a clean source of energy and has developed its own internal capability and experience in power generation from hydrogen. ESB's 1 MW electrolyser project at Aghada is expected to support further practical experience in renewable hydrogen production and use.

Leading Organisations

Ansaldo Energia, Siemens, Mitsubishi and GE are leading gas turbine producers with programmes to develop 100% hydrogen capable technologies. Bosch, Plug Power, Cummins and INNIO, among others, lead the reciprocating engine and fuel cell industries for stationary power supply.

Summary

Hydrogen can be used both to store energy over weeks, months and seasons at scale, and as a renewable fuel for dispatchable generation. Hydrogen power generation is a potential solution for net zero dispatchable generation in Ireland. However, considerable cost and technical challenges need to be overcome to scale this technology.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
6

Power Generation from Renewable Ammonia



Ammonia-fuelled reciprocating engine for power generation (© Copyright 2026 INNIO)

Ammonia (NH₃) is widely used in fertiliser production and is one of the world's most traded chemicals. In recent years, it has been proposed as a potential energy carrier because renewable ammonia can be produced by combining nitrogen from the air with renewable hydrogen generated through electrolysis. Ammonia can be used to generate power through direct combustion in reciprocating engines or gas turbines, or by cracking it into hydrogen and nitrogen and using the resulting hydrogen as a fuel.

Ammonia storage and transport are commercially mature, while renewable-ammonia power generation is currently assessed at approximately TRL 6. Development varies by pathway: direct combustion in small gas turbines and reciprocating engines is more advanced than utility-scale ammonia turbines and systems that crack ammonia to produce hydrogen for power generation.

Sample projects

In 2022, IHI in Japan successfully operated a 2 MW gas turbine fuelled exclusively by liquid ammonia, followed by long-duration testing in 2024 to assess its durability.

Cost

Renewable ammonia was priced at approximately US\$860 per tonne in Q1 2026. Power generation using this fuel remains costly and depends largely on fuel price, conversion efficiency and plant utilisation.

Timelines

IHI and GE Vernova are collaborating on a large-scale ammonia power-generation system, with commercialisation planned by 2030, while Mitsubishi Heavy Industries is developing a 40 MW ammonia gas turbine. Reciprocating-engine systems using ammonia are likely to achieve wider commercial deployment earlier than utility-scale ammonia turbines.

Potential to scale

Existing expertise and infrastructure for storing and transporting ammonia could support its use as a low-carbon fuel. However, significant health, safety and environmental risks must be managed. The emissions performance and durability of ammonia power-generation technologies also require further demonstration. Ammonia production costs would need to fall significantly for ammonia-based power generation to compete with other low-carbon options.

ESB Activity

ESB has assessed the potential for ammonia combustion in new and existing power stations and continues to monitor technology development, the maturity of the fuel supply chain, safety requirements and emissions performance.

Leading Organisations

Leading organisations include IHI, Mitsubishi Heavy Industries, INNIO, Jenbacher, MAN Energy Solutions, Amogy and 2G Energy.

Summary

Ammonia could serve as a renewable energy carrier because an established global supply chain already exists and it is easier to store and transport than hydrogen. However, renewable-ammonia power generation remains largely at the demonstration stage, with some smaller-scale systems approaching commercial readiness. Direct combustion in gas turbines and reciprocating engines is advancing, but widespread deployment of large utility-scale systems is unlikely until after 2030.

1. Low Carbon Generation (continued)

TRL
7-8

Future Solar Technologies

Solar technology is developing in several new directions, including agrivoltaics (co-use of land for both solar energy generation and agriculture), solar windows (electricity-generating glazing), floating solar, and even space-based solar power.

However, the most important near-term improvement for mainstream solar PV is likely to come from perovskite-silicon tandem cells. These cells place a thin perovskite layer on top of a conventional silicon cell. The perovskite layer is tuned to capture higher-energy light, while the silicon layer captures lower-energy light. Combined, these layers improve the total conversion efficiency of the panel and push module efficiency beyond what silicon alone can achieve. The technology is currently estimated at TRL 7–8, as it has moved from laboratory validation into pilot manufacturing and early commercial deployment.

The main benefit is higher power density. Mainstream silicon modules typically achieve efficiencies in the low-to-mid 20% range, while perovskite-silicon tandem modules are targeting module efficiencies of around 30% and have achieved higher efficiencies in demonstration settings. If proven reliable, this technology could generate more electricity from the same land or rooftop footprint.



ESB's solar farm at Bullstown, Co. Meath.

Sample projects

In April 2026, US company Tandem PV opened a commercial demonstration factory in California with an annual production capacity of 40 MW, having announced a 30.4% efficient perovskite-silicon demonstration module earlier in the year. The scale is small compared with mainstream solar manufacturing but is important because it demonstrates the move from laboratory cells toward repeatable module production.

Cost

Early tandem modules are likely to be more expensive than mature silicon panels as production volumes are still limited and long-term field performance is still being validated. The main commercial question is whether the efficiency gain is large enough to offset any module price premium.

Timelines

Perovskite-silicon tandem PV is moving from pilot production to early commercial deployment during the second half of the 2020s.

Potential to scale

The potential to scale is significant because tandem cells can build on existing silicon PV supply chains. The key challenges are improving stability, increasing manufacturing throughput and proving long-term durability under real-world operating conditions.

ESB Activity

ESB is expanding its solar PV generation portfolio. It is monitoring the development of commercial perovskite-silicon tandem panels and will consider them as they mature.

Leading Organisations

Leading organisations include perovskite specialists such as Oxford PV and Tandem PV, alongside large solar manufacturers such as LONGi, Hanwha Qcells, JinkoSolar and Trina Solar that are developing higher-efficiency solar technologies.

Summary

Perovskite-silicon tandem PV is one of the most important solar technology developments to watch because it offers a credible pathway to higher solar output from the same physical footprint. Other solar innovations may change where solar can be deployed, but tandem cells are more directly relevant to improving the performance of mainstream solar PV. The technology is not yet fully mature, but it could materially improve solar project economics if durability and manufacturing scale are proven.



1. Low Carbon Generation (continued)

TRL
6-7

Small Modular Reactors



A graphic of the SMR design Rolls-Royce is proposing to build in the UK (Credit: Rolls-Royce and the BBC)

Small Modular Reactors (SMRs) are nuclear fission reactors with a lower output than conventional nuclear power stations, typically up to 300 MWe per module.

Unlike a small reactor, defined solely by its lower generating capacity compared with a conventional nuclear power reactor, an SMR also relies on modular design, standardised factory production and shorter on-site construction. Much of the global pipeline comprises small reactor designs rather than a proven modular manufacturing model.

SMRs are being developed for electricity generation, industrial heat and district heating, desalination and large co-located users. Most near-term designs use proven light-water technologies, such as pressurised water reactors and boiling water reactors. More advanced modular reactor concepts, using gas-cooled, molten salt or fast reactor designs, remain less mature. Two SMR-class projects are operational, in China and Russia, while more than 80 designs are in development globally. While individual SMR-class reactors have reached commercial operation, the repeatable factory-production model assessed here remains at prototype or pre-commercial maturity (TRL 6–7), as the key economic claim - cost reduction through serial factory production - has not yet been demonstrated.

Sample projects

Two SMR-class projects are operational: Russia's floating Akademik Lomonosov and China's HTR-PM gas-cooled reactor at

Shidao Bay. These demonstrate commercial operation, but not the standardised, repeat-build manufacturing model underpinning SMR cost-reduction claims. China's 125 MWe LingLong 1 is undergoing commissioning and is expected to become the world's first commercial land-based SMR. Canada's Darlington New Nuclear Project is the most advanced Western commercial SMR project. Ontario Power Generation is developing the GE Vernova Hitachi BWRX-300, a 300 MWe boiling water reactor, at the existing Darlington nuclear site. It is expected to be operational by 2030, but as a first-of-a-kind project, it should not yet be taken as evidence that modular nuclear construction has achieved repeatable cost or schedule advantages.

Cost

SMR costs remain highly uncertain because there are few completed projects and no established fleet experience for repeat-build modular reactors. The economic case depends on whether factory fabrication, standardised design and series production can offset the loss of economies of scale associated with smaller unit sizes.

Timelines

The first Western commercial SMRs designed around a standardised, repeat-build model are expected to be operational around 2030. Broader deployment will be possible only if early projects demonstrate acceptable cost, delivery and regulatory performance. For Ireland, SMRs could not realistically contribute to the electricity system before 2040 given the current legislative prohibition, lack of nuclear regulatory infrastructure and long project development timelines.

Potential to scale

Globally, SMRs have attracted interest as a source of firm, low-carbon electricity, particularly in countries with nuclear capability or a need for additional dispatchable capacity. Their ultimate potential to scale will depend on the successful delivery and operation of first-of-a-kind projects, standardised licensing, supply-chain development, public acceptance, waste management arrangements and evidence that modular manufacturing can reduce costs. At present, SMRs have significant long-term potential, but the commercial viability of the standardised, repeat-build model remains unproven.

ESB Activity

ESB has no direct involvement in SMRs. In Ireland, nuclear fission for electricity generation is prohibited.

Leading Organisations

Leading organisations include GE Vernova Hitachi, Rolls-Royce SMR, NuScale Power, Westinghouse Electric, CNNC and Rosatom.

Summary

SMRs offer the promise of firm, low-carbon electricity from smaller and potentially more flexible nuclear units. While the sector is progressing from concept to first-of-a-kind deployment, the modular manufacturing and cost-reduction claims remain unproven until multiple standardised units are built and operated. Any potential nuclear programme in Ireland would require changes in government policy and legislation, a safety and regulatory framework, planning and emergency preparedness arrangements, fuel and waste management policies, and a long-term public engagement process. Taken together, SMRs are unlikely to provide a realistic option for Ireland before 2040.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

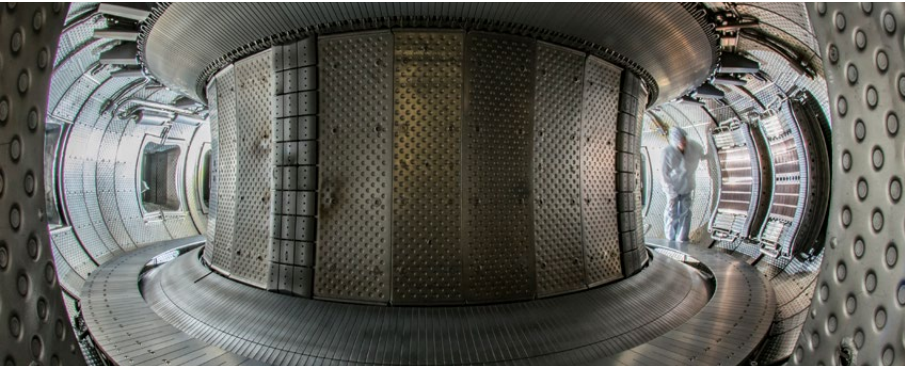
Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
5

Nuclear Fusion



Interior of the WEST tokamak vacuum chamber at CEA Cadarache, France (Credit: Christophe Roux, Wikimedia Commons, CC BY-SA 4.0)

Nuclear fusion combines light atomic nuclei to form heavier ones, releasing large amounts of energy in the process. Unlike nuclear fission (used in existing nuclear power plants), where atoms are split, fusion involves bringing atomic nuclei together. Fusion is the process that produces energy in the sun and other stars. The most promising combination for fusion on Earth involves fusing deuterium and tritium (both isotopes of hydrogen) to produce energy in the form of heat. This process requires extremely high temperatures (100 million °C), and achieving and maintaining these conditions is challenging.

Sample projects

There are a number of demonstration projects underway. Helion's 'Polaris' system is making progress and is being prepared to generate electricity. Helion has agreed a PPA with Microsoft for delivery in 2028. Commonwealth Fusion Systems (CFS) is one of the most advanced of the many privately held fusion companies. CFS is currently building a fusion demonstration machine at its headquarters in Massachusetts, with completion planned before 2030. CFS plans to build a 400 MW grid-scale fusion power plant in Virginia in the 2030s. Recently, China's Experimental Advanced Superconducting Tokamak reactor managed to contain the plasma needed for nuclear fusion for 17 minutes (the longest it has ever achieved), but the experiment was not designed to generate electricity.

Cost

The capital cost of fusion power needs to be significantly reduced for it to become commercially viable. However, several companies are working to commercialise fusion power and reduce costs through innovative reactor and magnetic-confinement designs. Fusion has been successful in raising funds. For example, Commonwealth Fusion Systems (CFS) has raised ~\$1bn to support the development of its ARC power plant programme. In Europe, ITER is making progress on developing the superconducting magnets and supporting systems needed for the first plasma and later deuterium and tritium operation.

Timelines

Deployment timelines are hard to forecast, but unless there is a technology breakthrough, fusion is at least a decade away from commercial viability. TRL is currently 5, with several pre-commercial projects in development.

Potential to scale

Globally, nuclear fusion offers the potential for clean and virtually limitless electricity generation.

ESB Activity

ESB has no direct involvement in nuclear fusion. However, it is actively tracking this technology.

Leading Organisations

Leading organisations include Commonwealth Fusion Systems (CFS), TAE Technologies, Helion Energy, General Fusion, Neo Fusion, Zap Energy, Tokamak Energy, First Light Fusion, Kyoto Fusionering, Focused Energy and Proxima Fusion.

Summary

Fusion remains one of the most ambitious long-term energy technologies under development. However, to become commercially viable it will need to overcome several significant engineering and financial challenges. Considerable public and private investment is being made to support its development. Despite this investment, fusion remains at least a decade away from commercial viability unless there is a technological breakthrough.

2 | Energy Storage

Energy storage is a critical enabler of an affordable, resilient, net zero electricity system. It allows renewable electricity to be shifted from periods of surplus generation to periods of high demand, low wind or low solar output. As Ireland and ESB move towards very high levels of variable renewable generation, storage will be needed across a range of technologies and durations. These range from short-duration batteries that support system services and daily balancing, to long-duration and seasonal molecular energy solutions, such as hydrogen and renewable fuels, that can maintain security of supply during extended renewable shortfalls. The technologies reviewed in this section are at different stages of maturity, but each could help address specific flexibility, resilience and decarbonisation needs in the future net zero power system.

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E-fuels	36



2. Energy Storage (continued)

TRL
8-9

Sodium-ion Battery Storage



Lab-scale precipitation reactor for the development of an active material for sodium-ion batteries (© Fraunhofer IFAM)

Sodium-ion batteries (Na-ion) are emerging as a sustainable and cost-effective alternative to lithium-ion (Li-ion) batteries. Sodium-ion holds potential as an alternative to lithium-ion because of more abundant raw materials, lower fire risk, a wider temperature operating range and higher depth of discharge capabilities. Sodium-ion batteries use sodium ions as their charge carriers and are more favourable than lithium-ion batteries in terms of their impact on mineral resource scarcity. For stationary storage, sodium-ion may be attractive where cost, safety, cycle life and supply-chain resilience matter more than maximum energy density. Sodium-ion for stationary and mobile storage (TRL 8-9) has begun to scale in recent years, led by projects in China.

Sample projects

Early deployment is being led by China. A 200 MW / 400 MWh hybrid lithium-ion and sodium-ion project in Yunnan includes 40 MWh of sodium-ion capacity supplied by HiNa Battery. A 50 MW / 100 MWh project in Hubei Province is one of the largest reported pure sodium-ion storage systems. In Europe, CATL and Alfen, a Dutch technology company, signed an MoU in 2026 to deploy 5 GWh of TENER Sodium systems, with initial deployments expected from 2027.

Cost

European project cost data remains limited due to a lack of projects. For grid-scale storage, sodium-ion batteries are expected to reach US\$55-70/kWh at the cell level in the next five years, but this does not represent the full installed cost of a utility-scale system. Sodium-ion may also offer lower operating and maintenance costs if long cycle life and safety claims are demonstrated in the field.

Timelines

Sodium-ion is moving from pilot production into early commercial deployment. CATL's Naxtra platform, launched in 2025, indicates increasing maturity in mobility applications, while its TENER Sodium energy storage system targets grid-scale storage with claimed long cycle life and a 25–30 year service life. The CATL–Alfen agreement suggests that European stationary storage deployments could begin from 2027.

Potential to scale

Sodium-ion has strong potential to scale because it can draw on abundant raw materials and adapt parts of the existing lithium-ion manufacturing base. The main constraints are lower energy density, limited European deployment history and the need to prove long-term performance in grid applications.

ESB Activity

ESB has shortlisted sodium-ion battery technology as a key storage technology to monitor. It will continue to assess the technology's suitability for grid-scale applications as commercial deployments and performance data emerge.

Leading Organisations

Leading organisations include CATL, BYD, HiNa Battery, Faradion and Natron Energy.

Summary

Sodium-ion batteries are one of the most advanced non-lithium battery technologies and are moving into early commercial deployment. Their lower energy density means they are unlikely to replace lithium-ion across all applications, but they could become a major complementary technology for stationary storage where cost, long cycle life and supply-chain resilience are most important. Given current commercial deployments and manufacturing investments, sodium-ion batteries have the potential to capture a significant share of the stationary energy storage market over the next decade.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
9

Flow Battery Storage



Flow Battery Storage (Credit: © Rongke Power (RKP))

Flow batteries are rechargeable batteries in which liquid electrolytes are stored in external tanks and pumped through electrochemical cells to charge and discharge. This separates power (determined mainly by the cell stack) from energy (determined mainly by the volume of electrolyte stored).

This makes flow batteries attractive for grid-scale applications requiring longer discharge durations, particularly in the 8–24 hour range. Flow battery technologies are being developed across a range of electrolyte chemistries, each at different TRL levels. Some examples include iron flow, iron-chromium, organic flow, zinc bromine and hydrogen/bromine chemistries. Vanadium Flow Batteries (VFBs) are currently the most mature (TRL 9) and are already commercially available.

Sample projects

China Huaneng Group has completed the main construction works on one of the world's largest vanadium redox flow battery projects. The project features a 200 MW / 1 GWh vanadium flow battery system (from Rongke Power) paired with a 1 GW solar farm. Invinity has secured a 2.1 GWh flow battery contract in Switzerland with FlexBase for data centre developments. In Australia, Idemitsu is proposing a 108 MW / 8-hour vanadium flow battery project in New South Wales.

Cost

Large-scale vanadium flow battery projects are currently reported in the region of €300–330/kWh, which remains higher than lithium-ion on an upfront capital-cost basis. However, costs vary significantly by project location, scale, duration and supply-chain maturity. Flow batteries may become more competitive at longer durations, particularly above eight hours, where their long cycle life, low degradation and separable power and energy sizing can improve whole-life economics.

Timelines

Vanadium flow batteries are now commercially available. A growth phase is expected between 2026 and 2030 as large projects are developed and manufacturing capacity scales. Other flow battery chemistries remain at lower maturity levels and are likely to progress through pilot and early commercial projects over the same period.

Potential to scale

Vanadium flow batteries have now passed the GWh-scale deployment threshold and are emerging as a viable option for long-duration grid storage. Around 1.1 GW of vanadium flow battery projects are reported to be under construction in China. Meanwhile, the number of announced projects suggests that several additional GWh-scale systems outside China could be operational before 2030. Scaling potential is strongest for applications requiring long duration, frequent cycling and low degradation.

ESB Activity

ESB is engaging with key flow battery OEMs. It is conducting a study to assess the feasibility of building a pilot or full-scale commercial flow battery storage system in Ireland. As part of the study, ESB is carrying out financial modelling to compare flow batteries with lithium-ion at longer durations.

Leading Organisations

Leading organisations include Invinity, CellCube, Largo, Sumitomo Electric, Rongke Power and ESS.

Summary

Flow batteries offer advantages over lithium-ion batteries for longer-duration storage, including longer output duration, increased stability, longer cycle life and low degradation. Vanadium flow batteries are the most mature flow battery technology and are now being deployed at GWh scale, particularly in China. However, upfront costs remain high and competitiveness is strongest at longer durations, particularly above eight hours. For shorter-duration applications, continued lithium-ion cost reductions may limit deployment unless flow batteries can demonstrate clear whole-life cost, safety or operational advantages.

2. Energy Storage (continued)

TRL
9

CO₂ Battery Storage



CO₂ battery storage (Credit: Energy Dome)

A CO₂ battery is a thermo-mechanical long-duration energy storage system that utilises compressed CO₂ to store and release energy when needed. The CO₂ battery is made primarily with standard industrial turbomachinery components. The use of CO₂ as the storage medium allows for high-density energy storage without the need for extremely low temperatures. The CO₂ changes between its gaseous and liquid states in the charging and discharging process. This process operates in a closed cycle with no CO₂ being emitted into the atmosphere.

CO₂ battery systems are designed mainly for 8–24 hour storage applications. This makes them potentially relevant for shifting renewable electricity over longer periods than conventional lithium-ion batteries typically serve. Their relatively large footprint means they are better suited to utility-scale sites than dense urban locations. The technology is currently at TRL 9.

Sample projects

Energy Dome's first commercial scale project (200 MWh) has been in operation in Sardinia, Italy, since 2025. Energy Dome's proposed project in Ireland is 23 MW / 200 MWh, with an offtake agreement in place with Google. Other Energy Dome projects in development include locations in the US, India and Australia.

Exa Energy and the China Huadian Corporation have completed a 100 MW / 1,000 MWh carbon dioxide energy storage plant in Western China.

Cost

Target costs for a full-scale 200 MWh project are approximately €200–220/kWh of storage capacity. Realised costs will depend on site requirements, supply-chain conditions and regional build-out costs.

Timelines

Energy Dome is developing projects in India and the USA that are expected to be completed in 2027. The proposed project at Rhode, Co. Offaly, is targeting completion in 2028.

Potential to scale

As projects are rolled out and performance data is validated, the scale and number of projects are likely to increase significantly. Google has announced its first partnership for long-duration energy storage with Energy Dome to support multiple commercial projects globally. Further projects are expected to be completed in China in the next five years.

ESB Activity

ESB and Energy Dome are continuing to examine the feasibility of developing a full-scale commercial CO₂ battery storage system in Ireland. ESB has visited Energy Dome's full-scale plant in Italy and completed technical evaluation and financial modelling to assess the technology's feasibility in the Irish market.

Leading Organisations

The leading technology providers include Energy Dome and Exa Energy.

Summary

CO₂ batteries are moving from demonstration to early commercial deployment, with utility-scale projects operating or under development globally. The technology uses established industrial components in a closed-loop CO₂ cycle and offers potential advantages including low fire risk, long asset life and synchronous grid connection. It may be better suited to 8–24 hour storage applications than conventional lithium-ion batteries, particularly where renewable electricity needs to be stored for longer periods. However, the technology has a large land footprint and a limited operating track record. Further commercial projects will be needed to validate performance and costs.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything	31
TRL 1-2	TRL 3-5	TRL 6-7	TRL 8	TRL 9			
Concept phase / research	Small scale prototype deployed in lab / controlled environment	Large scale prototype or subsystems deployed in controlled environment	Large scale prototype deployed in commercial type environment	Mature technology, deployed at scale in commercial type environment			

TRL
7-8

Liquid Air Energy Storage



Highview Power's Liquid Air Energy Storage plant under construction near Manchester, UK

Liquid Air Energy Storage (LAES) is a thermo-mechanical long-duration energy storage technology. It uses electricity to cool and liquefy ambient air at cryogenic temperatures of approximately -196°C. The liquid air is stored in insulated, low-pressure tanks and later warmed and expanded through a turbine to generate electricity.

The main advantages of LAES are its use of mature industrial components, its relatively flexible siting requirements and its potential for long asset life. Unlike pumped hydro storage or conventional compressed air energy storage, LAES does not require specific topography or underground caverns. It can therefore be located closer to grid constraints, renewable generation or demand centres. LAES is assessed as TRL 7–8, reflecting large-scale demonstration and early commercial deployment rather than fully mature deployment.

Sample projects

Highview Power's Carrington project at Trafford Low-Carbon Energy Park near Manchester is the leading commercial-scale LAES project. The plant is designed to provide 50 MW of output and 300 MWh of storage over six hours and construction is underway. It is expected to provide an important European commercial reference point for LAES.

The Super Air Power Bank project at Golmud in Qinghai Province, China, is one of the largest LAES projects reported globally. The facility has a power rating of 60 MW and storage capacity of 600 MWh, enabling up to 10 hours of discharge. It is co-located with a 250 MW solar PV plant.

Cost

The Long Duration Energy Storage (LDES) Council and the Electric Power Research Institute (EPRI) cost benchmarking work indicates that long-duration storage costs remain highly technology and configuration specific. For LAES and other multi-hour long-duration storage technologies, reported cost ranges remain materially higher than short-duration lithium-ion battery systems, particularly at early commercial scale. The current estimated range is approximately US\$158–471/kWh, with potential cost reduction dependent on project repetition, standardisation and supply chain development.

Timelines

LAES has moved beyond pilot scale and is entering early commercial deployment, but the operational track record remains limited compared with more established storage technologies.

Potential to scale

The theoretical scaling potential for LAES is strong because it is not geographically constrained and uses established industrial, storage and turbomachinery components. This should support repeatable deployment if standard plant designs can be developed.

ESB Activity

The Highview project is located adjacent to ESB's Carrington Power Station. ESB is engaged with the project and is monitoring its development as a potential reference case for long-duration energy storage.

Leading Organisations

Highview Power is the leading Western LAES developer, with commercial projects under development in the UK.

China Green Development Investment Group, working with Chinese research institutes and domestic suppliers, is advancing large-scale LAES deployment in China.

Summary

LAES is a promising long-duration storage technology with attractive siting flexibility, long asset life and the ability to provide low-carbon energy shifting when charged using renewable electricity. It is particularly relevant for power systems such as Ireland's, where renewable penetration is high and there is an increasing need for multi-hour storage. However, the technology remains at an early commercial stage, with relatively high costs, lower round-trip efficiencies than lithium-ion batteries, and a small number of large reference projects. The next phase of market confidence will depend on the successful operation and cost performance of early commercial plants.

2. Energy Storage (continued)

TRL
9

Thermal Energy Storage



Thermal energy stored for later use (Credit: Polar Night Energy)

Thermal Energy Storage (TES) stores energy as heat in a bulk storage medium such as molten salt, concrete, rock, sand or other high-temperature materials. The stored heat can support industrial processes, district heating or cooling. It can also be converted back to electricity through a power cycle.

TES is most mature where heat is the final output, particularly for high-temperature industrial heat. Electricity-to-heat-to-electricity systems are at an earlier stage of development but are being developed as a potential long-duration storage option for future electricity systems.

TES for industrial heat applications is commercially proven, with a TRL of 9. Grid-scale electricity-to-electricity TES systems are less advanced, with leading concepts generally around TRL 6, depending on configuration and project status.

Sample projects

Rondo Energy has moved industrial heat batteries towards commercial deployment, including a 100 MWh heat battery in California that entered commercial operation in 2025. In Hungary, Kyoto Group deployed a 56 MWh Heatcube system at KALL Ingredients in 2025. The project operates under a Heat-as-a-Service model that reduces upfront capital barriers for industrial customers.

Cost

At large scale, TES can achieve low storage costs because many systems use inexpensive and widely available storage media such as rock, brick, molten salt, sand or concrete. LDES Council and EPRI benchmarking indicates costs of US\$24–132/kWh, depending on the application, technology and discharge duration.

The economics are strongest where TES displaces fossil fuels for industrial heat, especially with low-cost renewable electricity or other supports. New commercial financing approaches, including heat-as-a-service models, can reduce upfront capital requirements for industrial customers. Electricity-to-electricity TES faces a more challenging value case because round-trip efficiency is generally lower than battery storage.

Timelines

Commercial TES systems for industrial heat are already operating at large scale across North America, Europe and Asia. Grid-scale electricity-to-electricity TES is less mature, with initial large-scale commercial demonstrators expected after 2030. Solid-media heat batteries, molten salt systems and pumped thermal energy storage are progressing in parallel.

Potential to scale

The potential for TES remains significant. For industrial users, TES can store low-cost renewable electricity as heat and reduce reliance on fossil fuel boilers. For the power system, TES could provide long-duration flexibility, reduce renewable curtailment and

support energy shifting over periods longer than those typically served by batteries. Industrial heat offers the strongest near-term opportunity, while grid-scale electricity-to-electricity TES may become more relevant over time.

ESB Activity

ESB is monitoring thermal energy storage developments, particularly where improvements in the technology can support industrial customer decarbonisation, demand flexibility and better use of renewable electricity. ESB's Smart Energy Services is working with customers to deploy low-carbon solutions such as TES.

Leading Organisations

Heat-focused developers include Rondo Energy, Polar Night Energy, Brenmiller Energy, Kraftblock, Migaldi, Kyoto Group and Antora Energy. Technology developers focused on utility-scale power output or power plant integration include Malta Inc. and Echogen Power Systems.

Summary

High-temperature industrial TES is mature and being deployed in industrial decarbonisation projects. Its strongest near-term role is likely to be replacing fossil fuel boilers in industry by storing low-cost renewable electricity as heat. Grid-scale electricity-to-electricity TES remains at an earlier stage. Large demonstrators are expected in the early 2030s, and commercial deployment is likely to depend on long-duration storage market signals.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
8

Iron-Air Batteries



Form Energy's Iron-Air battery factory in Weirton, West Virginia (Credit: Form Energy)

Iron-air batteries store energy through the reversible oxidation and reduction of iron — essentially charging and discharging by converting iron to rust and back again. The leading company is US-based Form Energy, which is targeting multi-day storage durations of up to around 100 hours using iron-air batteries. Form Energy's technology is currently at TRL 8, with commercial manufacturing underway and multiple utility-scale projects contracted.

Sample projects

Great River Energy is developing a 1.5 MW / 150 MWh proof of concept project in Minnesota.

Google has also reached an agreement with Xcel Energy to deploy a large 300 MW / 30 GWh iron-air battery system in Minnesota. In Ireland, FuturEnergy Ireland, in partnership with Form Energy, is developing a 10 MW / 1,000 MWh iron-air battery project in Co. Donegal.

Cost

There is insufficient commercial project information to validate current costs. Form Energy is targeting costs of approximately US\$20/kWh once manufacturing reaches commercial scale, but this remains a company target and has not yet been independently validated through multiple commercial projects.

Timelines

Large commercial scale projects ranging from 5 MW / 500 MWh to 15 MW / 1,500 MWh are expected in the 2027-2029 timeframe. Form Energy and FuturEnergy Ireland's 1,000 MWh project is expected to come online in 2029.

Potential to scale

If Form Energy achieves its technology and cost targets, the technology could scale significantly and reach GW-scale deployment. The Form Energy factory has already started commercial production and is expected to reach an annual production capacity of 500 MW by 2028.

ESB Activity

ESB will continue to monitor iron-air battery development, particularly the performance of early utility-scale projects and the potential relevance of multi-day storage to Ireland's high-renewables electricity system.

Leading Organisations

Form Energy is the leading organisation for this technology.

Summary

Iron-air batteries are among the most advanced non-lithium technologies for multi-day grid-scale energy storage. They are unlikely to compete with lithium-ion batteries for short-duration applications, but could become relevant where electricity systems need low-cost storage over 50–100 hours. However, deployment remains at an early stage. Real-world performance, efficiency and cost still need to be proven across multiple projects. If current projects prove successful, iron-air batteries could play a significant role in supporting electricity systems with high levels of renewable energy.

2. Energy Storage (continued)

TRL
8-9

Hydrogen Storage
(Large Scale)



Underground hydrogen storage in Austria (Credit: RAG Austria)

Large-scale hydrogen storage stores hydrogen gas for long durations, using above-ground tanks for small volumes or geological formations for very large volumes. TWh-scale storage is expected to require salt caverns, depleted gas fields, aquifers or lined rock caverns. Salt caverns are the most mature option (TRL 9). Depleted gas fields and porous reservoirs are less mature but may offer larger volumes and reuse existing gas infrastructure.

Sample projects

In April 2026, Plug Power supplied hydrogen to the H2CAST Etzel pilot in Germany, where two existing salt caverns and associated natural gas-storage infrastructure are being repurposed to demonstrate hydrogen storage at scale. In France, the HyPSTER project has completed around 100 hydrogen pressure cycles in a salt cavern, demonstrating the potential for cyclic hydrogen storage.

RAG Austria's Underground Sun Storage 2030 project has demonstrated hydrogen injection, storage and withdrawal in a depleted porous gas reservoir. The follow-on EUH2STARS programme runs to 2029 and aims to transfer its learning to other European underground hydrogen storage sites.

Cost

In Ireland, underground hydrogen storage costs are uncertain. However, depleted gas fields remain relevant because they could reuse existing offshore subsurface assets. Older estimates placed porous-media storage at around US\$0.2/kWh of hydrogen capacity and new salt caverns at US\$0.51/kWh. Recent studies use levelised cost per kilogram cycled. A 2024 Europe-wide analysis estimated levelised costs of US\$1.5/kg H₂ for porous-media storage, compared with about US\$0.8/kg H₂ for salt caverns (at sites with at least 0.5 TWh of working gas energy). The same analysis suggested that future storage costs could fall toward about US\$0.4/kg H₂ after several cycles of project development and operational learning. However, porous-media project costs remain sensitive to cycling frequency, cushion gas requirements and unrecoverable hydrogen.

Timelines

In Ireland, large-scale underground hydrogen storage is likely to be a post-2035 option. Ireland has no proven salt cavern storage sites and the suitability of offshore salt formations remains uncertain. Depleted gas fields may be more relevant, but commercial deployment will depend on hydrogen production volumes, infrastructure development, regulation, consenting and market support.

Potential to scale

Hydrogen storage could reach TWh scale in Ireland if renewable hydrogen production is developed at sufficient scale. This would support seasonal storage and dispatchable zero-carbon energy during extended low-renewable periods. The main constraints are geological suitability, cost, hydrogen availability and the development of a commercially viable market framework.

ESB Activity

ESB is a founding member of Kestrel Energy Storage, a joint venture proposing to redevelop the decommissioned Ballycotton gas reservoir in the Kinsale offshore area for large-scale energy storage. The project is considering initial natural gas storage in the early 2030s, followed by transition to renewable gas and hydrogen storage when sufficient volumes become available.

Leading Organisations

Leading organisations include Snam, Storengy and RAG Austria.

Summary

Hydrogen storage is a leading option for TWh-scale renewable energy storage over weeks, months and seasons. Salt caverns are the most mature underground storage option, while depleted gas fields may be particularly relevant for Ireland because of the potential to reuse offshore gas reservoirs and infrastructure. It could play an important role in a net zero electricity system, but it remains dependent on the development of low-cost renewable hydrogen, suitable geology, enabling infrastructure and a supportive market framework.

TRL
1-2

Concept phase /
research

TRL
3-5

Small scale prototype
deployed in lab /
controlled environment

TRL
6-7

Large scale prototype or
subsystems deployed in
controlled environment

TRL
8

Large scale prototype
deployed in commercial
type environment

TRL
9

Mature technology, deployed
at scale in commercial
type environment

TRL
6-9

Bio-derived
Renewable Fuels



HVO fuel trials at ESB's Aghada Power Station

Bio-derived renewable fuels can directly substitute for fossil fuels in transport, heating and electricity generation.

They can often be deployed with limited changes to existing infrastructure. Currently, most renewable diesel is produced by hydrotreating waste vegetable oils and animal fats using the mature HEFA (Hydro-processed Esters and Fatty Acids) process (TRL 9). This fuel is known as HVO (Hydrotreated Vegetable Oil).

There is limited global availability of sustainably sourced feedstocks such as waste animal fats and vegetable oils. Scaling renewable liquid fuel production will require alternative production pathways. These include gasification followed by Fischer–Tropsch synthesis using woody biomass and municipal solid waste (TRL 6), and Alcohol-to-Jet processes that convert grain- and waste-derived ethanol into sustainable aviation fuel (TRL 7–8).

Sample projects

In 2026, Iarnród Éireann undertook an HVO pilot on two formerly diesel-fuelled commuter trains in Cork. The pilot used about 100,000 litres of HVO.

The FLITE project is an advanced European Alcohol-to-Jet SAF project. In 2026, North Sea Port in Ghent was selected for a proposed commercial-scale facility using LanzaJet's process. The facility is expected to convert waste-derived ethanol into approximately 79,000 tonnes of sustainable aviation fuel per year.

Cost

Renewable liquid fuel costs depend strongly on production pathway and feedstock. HEFA-produced HVO is estimated at €1–€1.50/litre, while fuels produced through Fischer–Tropsch or Alcohol-to-Jet processes are currently two to five times more expensive. These comparisons are indicative, as advanced fuel pathways are at different commercial stages.

Timelines

HVO is commercially available, though sustainable feedstock supply is limited. Alcohol-to-Jet pathways are expected to enter early commercial deployment in the late 2020s, driven by sustainable aviation fuel mandates and the availability of waste-derived ethanol. Gasification followed by Fischer–Tropsch synthesis is likely to scale more slowly. Demonstration and first commercial projects are expected through the late 2020s and early 2030s.

Potential to scale

HEFA-produced renewable diesel has limited scale potential due to constrained recycled vegetable oil and animal-fat feedstocks. EU sustainability standards may further constrain feedstock availability. Gasification followed by Fischer–Tropsch synthesis and Alcohol-to-Jet pathways offer a much higher potential to scale because they can utilise larger volumes of woody biomass, municipal solid waste and waste-derived alcohol feedstocks. However, these pathways still face challenges linked to project finance, permitting, technology risk and securing long-term sustainable feedstock supply.

ESB Activity

ESB successfully tested low-carbon HVO in two of its power stations in 2026. It is examining its potential as a replacement for some fossil fuels currently used in its generation fleet.

Leading Organisations

HEFA-based renewable fuel producers include Neste, Eni and TotalEnergies. Alcohol-to-Jet developers include LanzaJet and SkyNRG. Developers active in gasification and Fischer–Tropsch waste-to-fuels pathways include Velocys.

Summary

Renewable diesel, particularly HVO, is a flexible replacement for fossil diesel and offers an attractive low-carbon option for existing asset owners. HEFA is commercially mature, but growth is constrained by limited sustainable feedstocks. Gasification followed by Fischer–Tropsch synthesis has greater scale potential, but remains more expensive and less commercially mature. Alcohol-to-Jet and gasification followed by Fischer–Tropsch synthesis could support future sustainable aviation fuel supply. However, both routes still require further commercial deployment, cost reduction and secure access to sustainable feedstocks.

2. Energy Storage (continued)

TRL
6-9

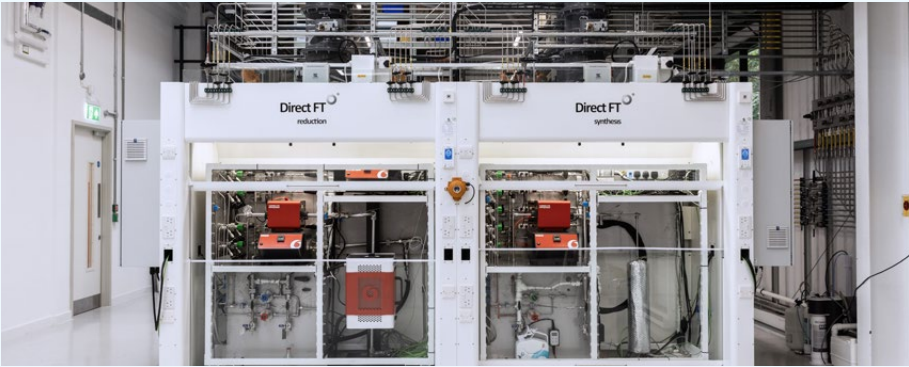
E-fuels

E-fuels (or electrofuels) are synthetic drop-in replacements for fossil liquid fuels. They are useful in applications where direct electrification is difficult, such as long-haul aviation. The most established production route combines renewable hydrogen from water electrolysis with biogenic or atmospheric CO₂. The Reverse Water Gas Shift process produces synthesis gas, which is then converted through Fischer-Tropsch synthesis into hydrocarbons such as e-diesel, e-gasoline and e-kerosene. An alternative route produces methanol as a final fuel or intermediate for e-kerosene or e-gasoline.

The conventional synthetic fuel production pathway is mature, but integration with renewable electricity and renewable hydrogen production has not yet reached large commercial scale. Fischer-Tropsch synthesis is at TRL 9, while the RWGS reaction is currently at a TRL of 6 or 7. Methanol-to-fuels pathways are typically assessed at around TRL 7.

Sample projects

Europe's largest e-fuel plant is INERATEC's ERA ONE plant in Frankfurt, Germany. Inaugurated in 2025, it has a nominal capacity of 2.5 ktonnes/year. INERATEC has also partnered with Rheinmetall on



UK-based Zero Petroleum's facility for producing liquid e-fuels using renewable electricity (Credit: Zero Petroleum)

GigaPtX, which aims to develop multiple European e-fuel plants to diversify liquid fuel supply and improve defence energy resilience.

China is leading e-methanol production. In July 2026, Carbon Recycling International installed the largest-of-its-kind e-methanol reactor at the Liaoyuan E-Methanol Project in Jilin Province, China. Once commissioned, the Tianying Group plant will produce 170 ktonnes/year of methanol using renewable hydrogen and captured biogenic CO₂.

Cost

The core synthetic fuel production processes are mature, but producing e-fuels using renewable hydrogen and variable renewable electricity remains costly. The European Union Aviation Safety Agency reports that the cost of e-fuel for aviation averaged approximately €7,520 per tonne in 2025, around twelve times the cost of conventional fossil jet fuel.

Timelines

Current production of e-diesel and e-kerosene remains limited to a small number of demonstration and early commercial facilities. Production is expected to increase by 2030 given the EU and UK e-fuel mandates for the aviation sector. In China, e-methanol is currently being produced at scale.

Potential to scale

There is a large potential to scale, and technology developers are working to address key barriers to wider deployment. Demand for e-jet fuel is expected to be supported by UK and EU sustainable

aviation fuel mandates, which introduce synthetic fuel sub-targets from 2030 and include financial penalties for non-compliance. In Ireland, this could create an initial e-jet fuel demand of approximately 14.9 kt/year by 2030.

ESB Activity

ESB is planning to develop a pilot project to produce around 400 litres/day of e-fuels. ESB is also actively participating in research projects across Ireland and Europe to foster the development of e-fuel technology.

Leading Organisations

Leading organisations include Sasol, Infinium, HIF, Topsoe, Honeywell UOP, Zero Petroleum, Johnson Matthey, Arcadia, Norsk-E, Nordic Electrofuels, INERATEC and Spark e-fuels.

Summary

E-fuels are synthetic drop-in alternatives to fossil liquid fuels, produced from renewable hydrogen and sustainable sources of CO₂. While the underlying chemical processes are well understood, integrated e-fuel production using renewable electricity remains at an early commercial stage and is currently expensive. E-fuels are therefore most likely to be used first in sectors where direct electrification is difficult, particularly aviation. Their long-term role will depend on access to low-cost renewable electricity, scalable renewable hydrogen production, sustainable CO₂ feedstocks and supportive regulation. They may also support energy security by enabling domestic or European production of strategic liquid fuels.



3 | The Empowered Customer

The term ‘empowered customer’ describes the shift from customers as passive users of electricity to active participants in the energy system. Enabled by digital platforms, smart devices, distributed generation and new market models, customers can increasingly generate, store, shift, export or manage energy in ways that support both their own needs and the wider electricity system. This is aligned with ESB’s net zero by 2040 strategy, which requires customer participation as well as investment in low-carbon generation, resilient networks and new energy services.

The technologies outlined in this section - including vehicle-to-everything, smart charging and balcony solar - show how households, businesses and communities can play a more active role in reducing demand peaks, integrating renewable generation, improving resilience and creating new sources of value in the transition to a net zero energy system.

Vehicle-to-Everything Charging and Smart Charging	40
Balcony Solar	42
Flexible Data Centres	43
Floating Data Centres	44
Anaerobic Digestion and Biomethane	45



3. The Empowered Customer (continued)

TRL
9

Vehicle-to-Everything
Charging and Smart
Charging

Smart charging manages EV demand in response to grid conditions and is commercially mature at TRL 9. Vehicle-to-everything charging (V2X) enables bidirectional power flow from an EV to a home, external load or the grid, where suitable infrastructure, customer permissions and market arrangements are in place. While the enabling technology is mature, markets and regulation for monetising these services are still emerging. Using V2X technologies, an EV can act as a battery storage system and participate in grid service activities such as demand time shifting, arbitrage or backup power.

Sample projects

Renault, Mobilize and The Mobility House in France, and Hegg with We Drive Solar in the Netherlands, offer residential Vehicle-to-grid (V2G) propositions using bidirectional Renault vehicles and compatible AC chargers. Octopus Energy and BYD have launched a UK V2G bundle including a BYD Dolphin, Zaptec Pro bidirectional charger and Octopus smart tariff.



A V2G enabled EV fast charger (Credit: Wikimedia Commons)

Cost

V2X chargers are more expensive than standard unidirectional chargers, with indicative costs ranging from €500–€2,000 for AC chargers and €3,000–€5,000 for DC chargers. AC systems rely on compatible EV inverters, while DC chargers include built-in inverters and can support a wider range of enabled vehicles.

Ireland does not yet have a dedicated export tariff for selling stored EV energy through V2X. Revenue is more likely to come from demand response, local flexibility markets and optimised charging/ discharging. In the UK, Octopus offers incentives through its V2G bundle, including free charging (up to a limit) and reduced charging tariffs.

Timelines

Smart charging is available today across most EVs and chargers where suitable tariffs and control systems exist. Some EVs can already support bidirectional charging using CHAdeMO, CCS2 or AC Type 2 connections with an appropriate charger, but customer propositions and market arrangements are still developing. Regulation from 2027 is expected to improve interoperability. VW Group, Mercedes, Volvo and Ford are planning further V2G offers in Europe.

Potential to scale

The scaling potential is significant as EV adoption grows and vehicles, chargers and aggregation platforms become interoperable. Smart charging is likely to scale first because it does not require

bidirectional hardware. V2G and wider V2X could add value for homes, fleets and the grid, but adoption will depend on vehicle compatibility, customer propositions and market access. In Ireland, near-term deployment is likely to focus on managed charging and fleets before wider residential V2G adoption.

ESB Activity

ESB Networks trialled domestic V2G chargers in 2019 and 2021 to test operability and local network impacts. ESB Smart Energy Services has also partnered with Mitsui and The Mobility House to provide aggregated smart charging revenue for An Post's commercial vehicle fleet. ESB is planning to further trial V2G/V2X technology.

Leading Organisations

Many EV OEMs have or plan to add V2X capability. Charger and solution providers include WallBox, Zaptec, Sigenenergy, Ambibox and EV-Tech/TMH, while TMH and Octopus/Kraken are leading EV flexibility optimisation.

Summary

Smart charging and V2X can provide important future grid flexibility as EV adoption grows. V2X offers are emerging in the US, Australia, Germany, the UK and France, but deployment remains limited. In Ireland, near-term value is strongest in managed charging and fleet applications, with broader V2X adoption dependent on compatible vehicles, customer acceptance and flexibility markets.



3. The Empowered Customer (continued)

TRL
9

Balcony Solar



Balcony solar in Germany

Balcony solar is a small-scale photovoltaic (PV) technology designed primarily for apartments, rented accommodation and homes where traditional rooftop solar is not feasible. A typical system consists of one or two solar panels that plug directly into a standard household socket, allowing users to generate electricity for immediate self-consumption. The technology provides a low cost and accessible entry point into solar energy. It offers relatively simple installation requirements, potential reductions in household electricity costs and greater customer participation in renewable generation.

Germany is the leading European market for balcony solar, and it surpassed one million registered systems in 2025. Growth has been supported by simplified regulation, falling equipment costs and strong consumer demand. The market is also moving into mainstream retail channels, with companies such as IKEA and Lidl offering complete balcony solar solutions. This technology has reached TRL 9.

Sample projects

In June 2025, IKEA Germany, in partnership with Svea Solar, launched a range of plug-in balcony solar systems, with optional battery storage. In August 2026, the UK government authorised the use of plug-in balcony solar.

Cost

Typical system costs vary depending on size and whether battery storage is included. Basic balcony solar systems (800–900 W) cost in the range of €400–€800. Systems with integrated battery storage cost in the range of €1,200–€2,500. Typical systems can generate approximately 700–1,000 kWh per year, with estimated payback periods of three to five years depending on electricity prices and household consumption.

Timelines

Balcony solar is already a mature consumer product, with significant deployment in markets such as Germany. Deployment is expected to expand over the next few years as regulation becomes more supportive across Europe. Over the medium term, balcony solar systems are likely to integrate more closely with battery storage and smart home energy management systems. In the longer term, aggregated systems could participate in grid flexibility markets and distributed energy resource programmes operated by utilities.

Potential to scale

Balcony solar has strong scaling potential. Its lower upfront cost compared with conventional rooftop solar, combined with growing availability through mainstream retailers, makes it more accessible than rooftop solar.

ESB Activity

ESB Networks is working with government to enable Irish consumers to use compliant plug-in solar systems and to ensure that network operations can take account of all microgeneration technologies.

Leading Organisations

EcoFlow and Anker SOLIX are leading suppliers of balcony solar kit systems for the European residential market. Zendure provides balcony energy storage through its SolarFlow system, while Svea Solar has helped mainstream the technology through partnerships such as IKEA Germany.

Summary

Balcony solar is one of the fastest-growing segments of distributed renewable energy in Europe. As regulations continue to evolve and mainstream retailers expand product availability, the technology is expected to be widely adopted across Europe.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything	43
TRL 1-2 Concept phase / research	TRL 3-5 Small scale prototype deployed in lab / controlled environment	TRL 6-7 Large scale prototype or subsystems deployed in controlled environment	TRL 8 Large scale prototype deployed in commercial type environment	TRL 9 Mature technology, deployed at scale in commercial type environment			

TRL
6-7

Flexible Data Centres



ESB's hydrogen fuel cell generating electricity for a data centre in Dublin

Data centres currently account for approximately 25% of Ireland's total metered electricity consumption, and demand is expected to grow further over the next decade. As renewable generation grows, there is increasing value in data centre loads that can respond to variable electricity generation conditions.

Data centre flexibility refers to the ability of a facility to adjust electricity demand without materially affecting the digital services it provides. This can be achieved through workload shifting, power capping (temporarily limiting maximum electricity draw), cooling flexibility and on-site batteries/generation. While real-time digital services have limited flexibility, a growing share of AI training, batch processing and backups may be suitable for more flexible scheduling. Software-based load shifting and carbon-aware workload scheduling are relatively mature, at TRL 7–8. More advanced grid-interactive hardware solutions, such as integrated UPS dispatch, batteries and thermal storage, are closer to TRL 6–7.

Sample projects

Recent demonstrations include Emerald AI's demand response trials in Arizona, Google's carbon-aware computing work and Microsoft's exploration of data centre battery systems for grid services. In the UK, National Grid has also demonstrated AI workload flexibility in a trial that reduced electricity consumption during periods of system stress.

Cost

The cost of enabling flexibility depends on the intervention. Software-based measures may have a relatively low capital cost but require coordination systems, contractual arrangements and customer agreements. Hardware-based flexibility is more capital intensive but can provide faster grid response. It may also create additional value where data centres can participate in demand response or system services markets.

Timelines

Flexible data centre operation is technically feasible and moving towards commercial implementation. Software-based load shifting and carbon-aware workload scheduling can be deployed quickly. More advanced flexibility is likely to develop over the next few years as market rules and grid service products evolve. Data centre operators are also looking for ways to support grid connection, renewable integration and local network management.

Potential to scale

The potential to scale is strongest for hyperscale and cloud operators with large portfolios of data centres, due to their

ability to shift workloads across regions. In Ireland, flexibility could be particularly valuable because large data centre loads are concentrated in areas with grid constraints. However, flexibility will be limited by latency, customer and contractual requirements, data sovereignty, cybersecurity and network constraints.

ESB Activity

ESB is part of the DCFlex programme run by the Electric Power Research Institute, which assesses data centre demand response, renewable integration, network support and flexibility markets. In 2026, ESB also used hydrogen fuel cells to demonstrate how on-site zero-carbon generation could reduce grid power demand from data centre operations.

Leading Organisations

Leading organisations include hyperscale cloud operators such as Google, Microsoft and Amazon, which are developing carbon-aware workload scheduling and battery-based flexibility. Emerging specialists such as Emerald AI are focused on using AI computing loads as a flexible demand response resource.

Summary

Flexible data centres can help manage peak demand, align computing loads with renewable generation and support system balancing. In Ireland, their relevance is increased by the scale and location of data centre demand, particularly where large loads are connected in constrained parts of the network. The near-term opportunity is likely to be strongest where software based flexibility can be deployed quickly. Hardware based flexibility may become more valuable as market rules and grid service products evolve.

3. The Empowered Customer (continued)

TRL
4-7

Floating Data Centres



High-end liquid-cooled server rack suitable for use in floating data centres.

Floating data centres host computing infrastructure on floating platforms located on water bodies. Facilities are typically mounted on barges, retrofitted ships or near-shore platforms. The main advantages are water-based cooling, reduced land use and proximity to grid or renewable infrastructure. They are less mature than flexible data centre operation: barge-based and water-cooled facilities are around TRL 7, while subsea or more exposed offshore concepts remain at an earlier stage at TRL 4–6.

Sample projects
Nautilus Data Technologies' Stockton 1 facility in California is a commercial example of a barge-mounted data centre. Built on a refurbished barge at the Port of Stockton on the San Joaquin River, it provides around 7 MW of critical IT load and uses river water for cooling. It supports high-density racks and achieves a low power usage effectiveness (PUE), meaning relatively little additional electricity is required for cooling and other facility overheads. The project demonstrates the potential for barge-mounted data centres to reduce land requirements and cooling energy demand. It also highlights the need for suitable port infrastructure, water access and grid connection.

Cost
Floating data centres may reduce some land and cooling-related costs, but these savings can be offset by higher platform, marine engineering, grid connection, insurance and maintenance costs. Cost competitiveness is highly site-specific and depends on whether land constraints, cooling requirements or access to low-carbon electricity create sufficient value.

Timelines
Near-shore or barge-based floating data centres could progress through pilots and early commercial deployments over the late 2020s where conditions are favourable. More ambitious offshore or subsea concepts are likely to require longer development timelines because of technical, operational and regulatory complexity.

Potential to scale
The potential to scale is more limited and more location-dependent than conventional land-based data centres. Floating platforms may be most relevant where land is constrained, water-based cooling is valuable and grid or renewable energy access is available near suitable ports, harbours or sheltered water bodies.

ESB Activity
ESB is monitoring developments in floating data centre technology. It is engaging with data centre operators, technology providers and infrastructure developers to understand emerging use cases, technical requirements and potential implications for grid connection, electricity networks and low-carbon power supply.

Leading Organisations
Leading organisations include Nautilus Data Technologies and Denv-R, which are developing waterborne or floating modular data centre concepts.

Summary
Floating data centres may offer long-term benefits where land availability, cooling demand and proximity to low-carbon electricity are major constraints. However, the technology remains less mature than flexible operation and faces additional marine engineering, permitting and operational challenges.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything	45
TRL 1-2 Concept phase / research	TRL 3-5 Small scale prototype deployed in lab / controlled environment	TRL 6-7 Large scale prototype or subsystems deployed in controlled environment	TRL 8 Large scale prototype deployed in commercial type environment	TRL 9 Mature technology, deployed at scale in commercial type environment			

TRL
9

Anaerobic Digestion and Biomethane



An anaerobic digester in Germany

Anaerobic Digestion (AD) is a mature technology that processes organic waste and agricultural feedstocks (e.g. silage) and converts them into usable products contributing to the circular economy. The two main products are digestate, which can be used as agricultural fertiliser, and biogas, which comprises around 60% methane and 40% biogenic CO₂. The biogas may be further upgraded to produce biomethane (>97% methane). Once it meets the gas grid standards, it can be compressed and injected directly into the gas grid. AD has been successfully deployed in many countries globally and is a very mature technology (TRL 9). Ireland has strong potential to deploy further AD to support the National Climate Action Plan. The National Biomethane Strategy for Ireland, which was published in May 2024, sets out an ambitious plan for industry growth by 2030.

Sample projects
Bia Energy owns and operates Ireland's largest AD plant in Huntstown, Co. Dublin. The feedstock includes waste products from the agricultural and food sectors. Currently, the facility upgrades the biogas to produce biomethane. The biomethane is then injected directly into the gas network, which was recently extended to the plant for this purpose.

Cost
The National Biomethane Strategy estimates the cost of producing biomethane at between €120-150/MWh for a 50 GWh plant.

Timelines
In Ireland, AD deployment is expected to increase significantly between 2026 and 2030, supported by the anticipated introduction of capital grants and the Renewable Heat Obligation in 2026-2027. The national target is 5.7 TWh of indigenous biomethane in 2030 as outlined in the Climate Action Plan.

Potential to scale
AD has strong potential to scale in Ireland. The target of 5.7 TWh of biomethane would cover 10% of Ireland's current overall gas demand. Denmark provides an example of deployment at scale: biomethane produced through anaerobic digestion currently meets more than 40% of the country's natural gas demand, with a target of 100% by 2030.

ESB Activity
ESB is actively reviewing developments in the anaerobic digestion industry in Ireland.

Leading Organisations
Leading developers include Bia Energy, Nephin Renewable Gas, Cycle0 Group, CarbonAMS, College Group and Greengate Biogas.

Summary
AD and biomethane have a positive outlook in Ireland because they can convert agricultural and food-sector feedstocks into renewable gas and useful digestate while supporting circular-economy outcomes. Ireland has a national target to produce 5.7 TWh of indigenous biomethane per year by 2030, supported by the National Biomethane Strategy and the planned Renewable Heat Obligation. Achieving this scale will require sustained policy support, investable project economics, access to suitable feedstocks, gas-grid connections and public acceptance of new AD infrastructure.

4 Carbon Capture, Utilisation and Storage Technologies

Carbon Capture, Utilisation and Storage (CCUS) refers to a family of technologies that capture carbon dioxide from industrial processes, power generation, bioenergy systems or directly from the atmosphere, before either using it in products or permanently storing it underground. For Ireland, CCUS could help address hard-to-abate industrial emissions, support security of supply in a net zero energy system and enable the development of future carbon management value chains. It is also central to negative emissions, particularly where biogenic or atmospheric CO₂ is captured and permanently stored. The technologies outlined in this section - point source carbon capture, BioEnergy Carbon Capture and Storage and Direct Air Capture - illustrate the different roles CCUS may play in reducing, avoiding and removing emissions on the pathway to net zero.

Point Source Carbon Capture	48
BioEnergy Carbon Capture and Storage	49
Direct Air Capture	50



4. Carbon Capture, Utilisation and Storage Technologies (continued)

TRL 9

Point Source Carbon Capture



The Ravenna Carbon Capture and Storage (CCS) plant located on Italy's east coast.

Point source carbon capture removes CO₂ from concentrated flue gases from industrial facilities and power stations. It can reduce emissions from hard-to-abate processes, but its climate benefit depends on capture rate, energy use, upstream emissions, transport and permanent storage.

Depending on the characteristics of the flue gas, different methods can be used to remove the CO₂. These are mostly classified as pre-combustion, oxy-combustion and post-combustion because it can be added without major upstream process changes. Amine-based chemical absorption is the most mature post-combustion option at TRL 9. Solid adsorption, calcium looping and membrane separation are at lower maturity levels.

Sample projects

Developed by Snam and Eni, Ravenna CCS is located on Italy's east coast. Its first phase covered capture from a 5 MW gas turbine, CO₂ transport and storage in a subsea reservoir. The project had a nominal capture capacity of 25,000 tonnes of CO₂ per year and utilised an amine-based solvent absorption technology from Mitsubishi. The plant was considered a pilot and operated for a year between 2024 and 2025. The project is expected to expand to phase 2, in which other carbon capture facilities will deliver the CO₂ to the injection point on-site.

Cost

The Global CCS Institute reports capture costs of around US\$35–40/tCO₂ for some coal power applications with CCS. Capture costs for natural gas power plants are typically higher, at around US\$80–120/tCO₂ captured, reflecting lower CO₂ concentrations and lower technology maturity in that application. Full-chain CCS costs also include CO₂ compression, transport, storage, monitoring and long-term liability.

Timelines

The Global CCS Institute reported global operational capture capacity of around 64 MtCO₂/year in 2025, with a further 44 MtCO₂/year under construction and more than 400 MtCO₂/year in development. Deployment is accelerating, but projects remain concentrated in jurisdictions with strong policy frameworks, shared CO₂ infrastructure and clear storage routes.

Potential to scale

Point source carbon capture has meaningful scaling potential in sectors with large, concentrated and hard-to-abate CO₂ emissions, particularly where emitters can connect to shared CO₂ transport and storage infrastructure. Deployment is being supported by industrial cluster models in the UK, EU Innovation Fund projects and carbon pricing. In Ireland, scaling potential will depend on identifying suitable industrial emitters, developing or accessing CO₂ transport and storage infrastructure, and creating a policy and commercial framework that supports investment.

ESB Activity

ESB participated in the Horizon Europe REALISE CCUS consortium, which tested new absorbent materials and assessed carbon capture applications for industrial and energy-sector emissions. The consortium included research institutions and industry partners such as University College Cork, TU Delft, Bord Gáis Energy and Ervia.

Leading Organisations

Leading organisations include capture technology providers such as Mitsubishi Heavy Industries, Aker Carbon Capture, Carbon Clean and Capsol Technologies. Major project developers and storage operators include Equinor, Shell, Eni, Snam, TotalEnergies, ExxonMobil and BP.

Summary

Point source carbon capture can reduce emissions from industrial and power-sector processes where direct electrification or fuel switching is difficult. Amine-based post-combustion capture is the most mature route, while adsorption, membranes and calcium looping remain at earlier stages of deployment. Costs depend strongly on CO₂ concentration, operating profile and access to transport and storage infrastructure. The technology is likely to scale first in industrial clusters with shared CO₂ networks and supportive policy. For the power sector, an important challenge is maintaining efficient capture performance and project economics when plants operate flexibly or intermittently.

TRL 1-2 Concept phase / research TRL 3-5 Small scale prototype deployed in lab / controlled environment TRL 6-7 Large scale prototype or subsystems deployed in controlled environment TRL 8 Large scale prototype deployed in commercial type environment TRL 9 Mature technology, deployed at scale in commercial type environment

TRL 8-9

BioEnergy Carbon Capture and Storage



Carbon stored in the form of Biochar (Credit: Biogreen Energy)

BioEnergy Carbon Capture and Storage (BECCS) combines bioenergy with carbon capture and permanent storage to deliver carbon-negative emissions. Biomass absorbs CO₂ as it grows; if the CO₂ released during bioenergy production is captured and permanently stored, the process can deliver certified carbon removals, subject to robust sustainability and certification rules.

BECCS can be applied to several bioenergy processes, including biomass combustion, bioethanol production and biomethane upgrading. Capture technology depends on the CO₂ stream. Dilute flue gases from biomass combustion typically require post-combustion capture such as amine absorption. Bioethanol production and biomethane upgrading can provide more concentrated biogenic CO₂ streams that may be easier and cheaper to capture.

BECCS is moving from demonstration to early commercial deployment, with integrated projects typically assessed at around TRL 8-9, while some component capture technologies are already more mature.

Sample projects

The 50 MW Mikawa biomass power plant in Japan began BECCS operations in 2020, using amine-based capture on flue gas from a plant fuelled by palm kernel shells.

In Sweden, the Stockholm Exergi BECCS project is under construction. It aims to capture around 800,000 tonnes of biogenic CO₂ per year from an existing biomass-fired combined heat and power plant and is scheduled to be commissioned in 2028.

Cost

Costs vary significantly depending on the CO₂ source, capture technology, plant scale, transport distance and storage route. CDR.fyi reports an average 2030 breakeven cost of around US\$182/tCO₂ for BECCS removals. This is broadly consistent with values reported by other industry sources. Capture is generally lowest cost where the CO₂ stream is already concentrated, such as bioethanol production. It is more expensive for dilute combustion flue gases from biomass power or heat plants. Biomethane upgrading can also provide relatively concentrated biogenic CO₂, although aggregation and transport may add cost for smaller distributed sites.

Timelines

Small-scale and demonstration facilities are currently operating across the globe. Commercial large-scale plants are being constructed and are expected to be operational by the end of the decade. No official announcements have been made for Ireland.

Potential to scale

In Ireland, BECCS potential is likely to be concentrated around a limited number of biogenic CO₂ sources. The Edenderry biomass power plant represents the most obvious large single point source.

Ethanol production and distilleries could also provide relatively concentrated biogenic CO₂ streams, although typically at smaller scale. Biomethane plants may become an important distributed source of biogenic CO₂ as the sector grows, but their dispersed nature would make aggregation, transport and storage more challenging.

ESB Activity

ESB does not operate biomass power plants but is monitoring BECCS developments. It is assessing the potential relevance of carbon-removal technologies for Ireland's future net zero energy system.

Leading Organisations

Leading organisations include capture technology providers such as Mitsubishi Heavy Industries, Capsol Technologies, Aker Carbon Capture and Honeywell UOP. Major energy companies such as Shell, ExxonMobil and Chevron are developing CO₂ transport and storage solutions relevant to BECCS deployment.

Summary

BECCS could play an important role in delivering certified carbon removals for residual emissions in hard-to-abate sectors. Early commercial projects are being developed internationally, with carbon-removal credits expected to become available from larger BECCS projects later this decade. In Ireland, the opportunity is more limited and will depend on large sustainable biogenic CO₂ sources, access to CO₂ transport and storage infrastructure, and robust carbon accounting.

4. Carbon Capture, Utilisation and Storage Technologies (continued)

TRL
5-8

Direct Air Capture

Direct air capture (DAC) refers to technologies that remove CO₂ directly from ambient air. Because CO₂ makes up only around 0.04% of air, DAC is energy intensive compared with capture from concentrated industrial CO₂ sources. The two main technology routes are solid-sorbent systems, generally at TRL 7–8, and liquid-solvent systems, generally at TRL 5–6. Both use cycles of CO₂ capture and release, with electricity and/or heat required to regenerate the capture material. DAC is attracting growing policy and corporate interest because it can provide measurable carbon removals when the captured CO₂ is permanently stored.



Direct air capture unit (Credit: SYNAERGY / Trinity College Dublin)

Sample projects

1PointFive's STRATOS plant in Texas is designed to capture up to 500 ktCO₂ per year and is expected to become the largest DAC facility globally once operational. Climeworks' Mammoth facility in Iceland is currently one of the largest operational DAC plants and provides an important reference project for solid-sorbent DAC with geological storage.

Cost

DAC remains expensive, with current costs often reported in the several-hundred-dollar-per-tonne range. Recent contracted removal prices are around US\$500/tCO₂. Significant cost reduction will depend on larger deployments, cheaper low-carbon energy and standardised plant designs.

Timelines

DAC is moving from small commercial facilities towards first-of-a-kind large-scale projects in the late 2020s. Larger plants such as STRATOS should provide important cost and performance data. Wider deployment will depend on strong carbon-removal markets, access to low-carbon energy, permanent storage infrastructure and supportive policy frameworks.

Potential to scale

DAC has high theoretical scaling potential because it is not tied to a specific industrial emissions source. However, practical deployment will be constrained by cost, low-carbon energy availability and CO₂ transport and storage infrastructure. The development of credible long-term markets for certified removals will also be a factor.

ESB Activity

ESB is due to conduct a three-month trial of a DAC unit from Trinity College Dublin at Aghada Power Station.

Leading Organisations

Leading organisations include Climeworks, Global Thermostat, 1PointFive, CarbonCapture, Holocene and Heirloom.

Summary

DAC can deliver measurable carbon removals by capturing CO₂ directly from ambient air and permanently storing it underground. However, the technology remains expensive and energy intensive. Deployment is dependent on access to low-carbon electricity, suitable CO₂ transport and storage infrastructure, robust certification frameworks and supportive policy. In Ireland, commercial-scale DAC would require a clear route for permanent CO₂ storage, either through future domestic policy changes or access to storage infrastructure elsewhere.



5 | Grid Technologies

Grid technologies are the physical, electrical and digital systems that allow electricity networks to transport, manage and balance power safely, efficiently and reliably. They will become increasingly important as ESB implements its net zero by 2040 strategy. The grid will need to support the connection of more renewable generation, increased electrification and continued network resilience. The technologies reviewed in this section illustrate the range of innovations that may be needed to strengthen and modernise the grid. They could help move large volumes of renewable electricity over long distances, maintain system stability, optimise existing network capacity and reduce the climate impact of essential grid assets.

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5. Grid Technologies (continued)

TRL
7

High Temperature Superconductor Cables



The SCARLET superconductor demonstration project, Blyth, UK (Credit: SuperNode)

A high temperature superconducting cable uses materials that become superconducting when cooled by liquid nitrogen to approximately -180°C. The term 'high temperature' is relative, as these cables still require cryogenic cooling but operate at higher temperatures than earlier superconducting materials.

For transmission applications, they can carry very high power through a compact cable with low electrical losses, although cooling-system energy demand and operational complexity must also be considered.

They have only been used in relatively short connections to date, and a medium-distance transmission demonstration has yet to be developed. For transmission-scale applications, the technology is assessed at approximately TRL 7.

Sample projects

The Shingal project in South Korea connects the 154 kV Shingal and Heungdeok substations over a distance of 1 km. Commissioned in 2019, it has operated as planned and Korea Electric Power Corporation is investigating further applications. SuperNode has demonstrated the transmission of 5,000 amps through 30 m of a new cable design using a polymeric cryostat at the Blyth technology centre in the UK. The SCARLET project, funded through Horizon Europe, involves 15 industry partners developing common

standards for high-power superconducting cables and demonstrating full-scale bipolar 1 GW power transfer.

Cost

OEMs estimate that high temperature superconducting cables could be cost-competitive with conventional alternatives in some applications, particularly where space constraints or high power transfer requirements are important. However, these estimates have not yet been validated through large-scale transmission deployment. Cooling systems, maintenance requirements and long-term reliability will be key cost factors.

Timelines

High temperature superconducting cables are likely to remain focused on targeted demonstration and early deployment applications over the next decade, particularly where compact, high-capacity connections are valuable. Further progress will depend on larger-scale transmission demonstrations, standardised cable and cryogenic-system designs, and the establishment of long-term ageing test facilities.

Potential to scale

High temperature superconducting cables could scale in applications where compact, high-capacity connections are required. These include urban networks, constrained corridors, offshore transmission and high-capacity interconnection. Their wider deployment will depend on standardisation, proven cryogenic system reliability and demonstration of long-term performance at transmission scale.

ESB Activity

ESB does not currently have any active projects related to superconducting transmission lines. It is maintaining a watching brief through regular engagement with OEMs, other utilities and experts from the International Council on Large Electric Systems (CIGRE). Some newer ESB Networks HV and MV underground cable installations have used ducted construction since the early 2000s. This could reduce the disruption associated with future cable replacement, although practical feasibility would depend on cable design, cooling infrastructure and network configuration.

Leading Organisations

Leading organisations include VEIR, NKT, SuperNode, Fujikura, Nexans, THEVA, Korea Electric Power Corporation and selected cryogenic-system suppliers.

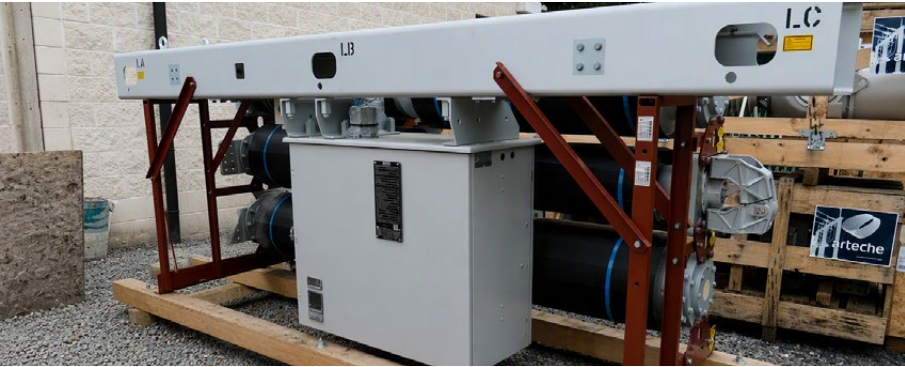
Summary

High temperature superconducting transmission cables offer low electrical losses, compact cable dimensions and the potential to transfer much larger amounts of electricity than conventional cables in constrained locations. If the technology can be demonstrated at larger scale, standardised and supported by reliable cryogenic systems, it could help enable high-capacity grid connections, renewable integration and improved grid reliability.

TRL 1-2 Concept phase / research TRL 3-5 Small scale prototype deployed in lab / controlled environment TRL 6-7 Large scale prototype or subsystems deployed in controlled environment TRL 8 Large scale prototype deployed in commercial type environment TRL 9 Mature technology, deployed at scale in commercial type environment

TRL
6-9

SF₆ Free Equipment



ESB Networks' first 110 kV non-SF₆ circuit breaker during installation at Dunfirth 110 kV Substation in Co. Kildare in 2026

Sulphur hexafluoride (SF₆) is widely used as an insulating and arc-quenching gas in medium-voltage and high-voltage electrical equipment, including switchboards, circuit breakers, metal-enclosed switchgear and gas-insulated switchgear.

However, SF₆ has a very high global warming potential and long atmospheric lifetime. Its replacement is an important priority for electricity networks and equipment manufacturers. SF₆ free switchgear is at TRL 8–9 for medium-voltage applications, while high-voltage solutions are generally at TRL 6–8 and still moving through pilot and early deployment stages.

Network operators and manufacturers are developing and deploying alternatives that can maintain safety and reliability while reducing greenhouse gas risk. The main technology pathways include:

- Air-insulated switchgear: uses air as the insulation medium instead of SF₆.
- Gas-insulated switchgear with alternative gases: uses dry air, nitrogen, synthetic air or lower global warming potential gas mixtures as the insulation medium.

- Solid-insulated systems: use solid insulation materials to provide electrical insulation.
- Vacuum switching: uses a vacuum interrupter to extinguish arcs, often combined with air, solid or gas insulation.

Sample projects

Across Europe, network operators are trialling SF₆ free switchgear across both distribution and transmission applications. E-REDES in Portugal has tested medium-voltage equipment using vacuum switching and solid insulation. E.ON grid operators are piloting SF₆ free solutions at MV and HV levels. Other operators, including i-DE and Enedis, are also testing dry-air, vacuum and alternative gas-insulated equipment with multiple manufacturers.

Cost

Commercial cost evidence remains limited because many projects are still at pilot or early deployment stage. SF₆ free equipment is likely to carry an initial cost premium, particularly at higher voltages. Whole-life costs may improve as manufacturing scales, carbon and regulatory risks are reduced, and requirements for SF₆ handling, leakage monitoring and end-of-life recovery are avoided.

Timelines

Medium-voltage SF₆ free equipment is already commercially available for many applications. Higher-voltage solutions are expected to move from pilots to wider deployment over the late 2020s as performance, safety and lifecycle evidence builds.

Potential to scale

The potential to scale is high, particularly in medium-voltage networks where commercial products are already available.

ESB Activity

In 2026, ESB Networks procured its first non-SF₆ MV GIS boards and 110 kV circuit breakers following an engineering assessment.

Leading Organisations

Leading organisations include Hitachi Energy, ABB and Schneider Electric.

Summary

Distribution system operators are beginning the transition towards SF₆ free networks. Wider deployment will require close collaboration with manufacturers, robust field evidence, and further trials to demonstrate that new systems can match existing equipment in reliability, safety, cost-effectiveness and lifecycle performance. In Europe, the move towards SF₆ free equipment is being accelerated by the EU F-gas Regulation. This progressively restricts the use of SF₆ based switchgear. However, for some high-voltage applications, particularly above 145 kV, alternatives are still maturing.

5. Grid Technologies (continued)

TRL
8

Dynamic Line Rating



ESB Networks drones placing DLR sensors on power lines

Overhead line ratings define the safe operating limits for how much power a line can transmit. Traditional static or seasonal ratings use conservative assumptions about ambient temperature, wind speed and solar heating, which can leave capacity unused for much of the year.

Dynamic Line Rating (DLR) estimates capacity in real time or near real time by using actual weather and conductor conditions, including temperature, wind, solar radiation and conductor sag.

The application of DLR can increase the usable capacity of existing transmission assets, depending on network characteristics and local weather conditions. Studies and vendor deployments have reported typical capacity increases of around 10–30% compared with static ratings. Higher uplifts are possible during favourable cooling conditions. DLR is a mature technology. ENTSO-E's Technopedia classifies it as TRL 8 for applications by European transmission system operators.

Sample projects

Elia (Belgium) has used DLR on cross-border overhead lines to support additional import capacity following the closure of Belgian nuclear generation. Under favourable cooling conditions, monitored line ratings exceeded seasonal ratings by a substantial margin.

In Northern Ireland, Heimdall Power installed NIE Networks' first DLR sensors in Tyrone in 2026, using drones to mount sensors on live transmission lines.

ESB Networks has successfully deployed DLR sensors on sections of the 220 kV transmission network in north Dublin.

Cost

Indicative DLR costs are highly site-specific. Reported installation costs are approximately US\$16,000–56,000 per mile for deployments that improve ratings by around 10% compared with static line ratings. Where thermal line limits are a binding constraint, DLR can provide a relatively low-cost means of unlocking incremental capacity and reducing congestion. It can also defer more capital-intensive reinforcement measures such as reconductoring or line rebuilding. However, benefits are not uniform and depend on local weather patterns and the condition of existing infrastructure.

Timelines

EirGrid and ESB Networks are expanding the use of dynamic line rating on parts of the transmission network. This will provide greater real-time visibility of line performance, helping to unlock additional capacity on constrained circuits and support periods of increased renewable generation. Adoption is expected to increase in the near term as transmission operators seek faster, lower-cost ways to release capacity on constrained lines while longer-duration reinforcement is planned and delivered.

Potential to scale

DLR can be applied to suitable overhead lines and is particularly effective in windy areas, where conductor cooling can increase available capacity. However, it does not always increase capacity and cannot remove constraints caused by substations, transformers, protection systems or downstream bottlenecks.

ESB Activity

ESB Networks and EirGrid are working with Heimdall Power to deploy dynamic line rating technology across the Irish transmission network. DLR also features in ESB Networks' innovation portfolio, using meteorological parameters and conductor state to determine capacity on an hourly and day-ahead basis. For Ireland, the technology is particularly relevant where renewable curtailment, connection delays and network congestion are linked to constraints on existing overhead lines. DLR can support faster utilisation of existing transmission assets while longer-term reinforcement is developed.

Leading Organisations

Leading organisations include DLR sensor, software and analytics providers such as Heimdall Power, Ampacimon, LineVision, Siemens and Enline.

Summary

Dynamic line rating is a mature grid-enhancing technology with strong near-term relevance for Ireland. It can unlock additional transfer capability on existing overhead lines, support renewable integration and help defer more capital-intensive reinforcement where line thermal limits are a binding constraint.

TRL
1-2

Concept phase / research

TRL
3-5

Small scale prototype deployed in lab / controlled environment

TRL
6-7

Large scale prototype or subsystems deployed in controlled environment

TRL
8

Large scale prototype deployed in commercial type environment

TRL
9

Mature technology, deployed at scale in commercial type environment

TRL
7-8

Grid Forming Inverters



Inverter of solar cell power generation system

Grid forming inverters help keep the electricity system stable as more power comes from renewables, batteries and other technologies connected through power electronics. Most inverters today are 'grid following', meaning they rely on the existing grid to provide a stable voltage and frequency signal.

A grid forming inverter can instead create its own voltage and frequency reference. This is especially useful in weaker parts of the network or at times when there is less conventional generation online. This means grid forming technology can help manage sudden changes in frequency or voltage, thereby supporting areas with high levels of renewable generation and improving the resilience of the power system.

Grid forming control is therefore becoming an important tool for operating a low-carbon electricity system. In 2026, EirGrid assessed grid forming batteries, HVDC interconnectors and STATCOMs as TRL 8. Grid forming wind generation was assessed at TRL 7, reflecting its comparatively earlier stage of commercial deployment.

Sample projects

Blackhillock in Scotland is a 300 MW / 600 MWh grid forming battery project developed by Zenobē, with an initial 200 MW / 400 MWh phase commissioned in 2025. It provides active and reactive power stability services, synthetic inertia and short-circuit contribution to support system stability in a low-inertia grid.

Föhren in Germany is a 21 MW / 55 MWh grid forming battery project commissioned in 2025 through the Westnetz-led SUREVIVE project. It provides frequency and voltage support and can black-start the local distribution network, demonstrating the resilience value of grid forming batteries.

Cost

The incremental cost of grid forming compared with grid following inverters is primarily driven by software, system integration and testing rather than hardware. For battery energy storage systems, grid forming functionality is estimated to increase capital costs by around 5%.

Timelines

In 2026, EirGrid and SONI stated that they plan to introduce voluntary grid forming requirements into the Grid Code and to conduct technology trials. These trials will include a grid forming HVDC trial on the Celtic Interconnector and a power park module trial through the Qualification Trial Process, helping to inform future Grid Code requirements.

Potential to scale

Grid forming technology is being demonstrated through a growing number of trials and commercial projects worldwide and has significant potential to scale. However, wider deployment is constrained by the lack of harmonised standards for testing, performance assessment and compliance validation.

ESB Activity

ESB does not currently have an active grid forming project. However, ESB operates more than 300 MW of battery energy storage across multiple sites and continues to expand its storage portfolio, which could provide a platform for future deployment.

Leading Organisations

Leading suppliers of grid forming technologies for battery energy storage systems include Tesla, SMA and Sungrow. In HVDC transmission, the leading suppliers are Hitachi Energy and Siemens Energy. In wind generation, the OEMs developing grid forming capabilities are Siemens Gamesa and GE Vernova.

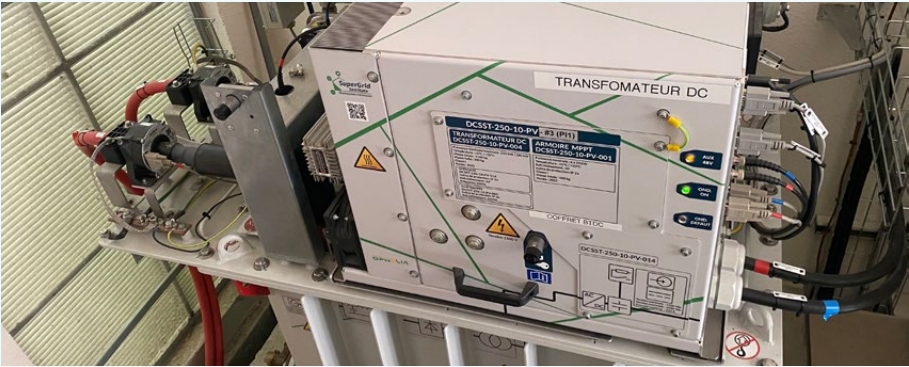
Summary

Grid forming technology is becoming an important enabler of high-renewable electricity systems. It is already close to commercial maturity in batteries, HVDC and STATCOMs, while wind applications are still developing. For Ireland, grid forming capability could support system stability as conventional generation runs less often and renewable penetration increases.

5. Grid Technologies (continued)

TRL
6-7

Medium Voltage Direct Current



Medium Voltage Direct Current demonstration unit (Credit: SuperGrid)

AC electricity changes direction many times per second, while DC electricity flows in one direction.

DC is becoming more important because many modern technologies either produce, store or use electricity in DC form, including solar PV, batteries, data centres, electronics and many EV charging systems. This creates opportunities for Medium Voltage Direct Current (MVDC) links to connect renewable generation and large electricity users more efficiently or controllably in some circumstances.

Because most electricity networks are still AC-based, an MVDC link uses converters at each end to connect DC circuits or equipment to the wider AC system. These converters enable precise control of power flows and may allow more power to be transferred through existing conductors than with conventional AC operation. Existing AC circuits may also be converted to DC service, increasing network capacity while minimising the need for new lines and associated infrastructure. High Voltage Direct Current (HVDC) is not covered here because it is already a mature technology used by transmission system operators and interconnectors.

MVDC remains an emerging technology within electricity distribution networks. While several pilot projects and demonstrations have been undertaken internationally, large-scale deployment remains limited. Based on recent demonstration projects, MVDC distribution systems appear to sit broadly within TRL 6–7.

Sample projects

ANGLE-DC (SP Energy Networks, UK) converted an existing 33 kV circuit from AC to DC. The project demonstrated an approximately 23% increase in transfer capability, while providing controllable bidirectional power flow and voltage support.

The OPHELIA project in France demonstrated an MVDC architecture for photovoltaic plants using a ±5 kV/10 kV collection network along linear infrastructure corridors.

China has undertaken significant MVDC distribution network development, with projects such as the Suzhou Wujiang and Zhuhai demonstrator projects. The Suzhou Wujiang project operates at multiple DC voltage levels (±10 kV, ±750 V, and ±375 V), demonstrating multi-voltage MVDC distribution architectures.

Cost

There is currently no widely accepted cost benchmark for utility-scale MVDC distribution systems. Project costs are highly site-specific and depend on factors such as network design, voltage level, power rating, protection requirements, and the extent to which infrastructure is newly constructed or repurposed.

Timelines

While converter technology is available, utility-scale MVDC distribution links in Europe remain largely at the demonstration stage. Wider adoption is likely to depend on standardisation, technology maturity and stronger use cases for high-power DC demand.

Potential to scale

MVDC could scale where existing AC circuits can be repurposed, or where large DC loads such as data centres, EV charging hubs and renewable generation clusters justify dedicated DC infrastructure.

ESB Activity

ESB does not currently have an active MVDC project.

Leading Organisations

MVDC converters: Hitachi Energy, GE Vernova, Siemens Energy, Mitsubishi Electric.

Solid-state transformers (SSTs): Eaton, Hitachi Energy, Delta Electronics.

DC switchgear and protection: Hitachi Energy, Siemens Energy, Schneider Electric.

Summary

MVDC remains an emerging distribution-network technology with potential to increase capacity within existing corridors and support high-power DC demand. However, wider deployment depends on mature DC protection, switchgear and proven business cases.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything
TRL 1-2 Concept phase / research	TRL 3-5 Small scale prototype deployed in lab / controlled environment	TRL 6-7 Large scale prototype or subsystems deployed in controlled environment	TRL 8 Large scale prototype deployed in commercial type environment	TRL 9 Mature technology, deployed at scale in commercial type environment		

TRL
7-9

Advanced Reconductoring and Grid Capacity Enhancement



ESB Networks improving overhead power lines

Advanced reconductoring involves replacing the wires on existing overhead electricity lines with higher-capacity conductors, while retaining much of the existing infrastructure including towers, foundations and rights of way.

Modern conductors utilise innovative materials such as carbon fibre composites, aluminium zirconium alloys and other high temperature low-sag (HTLS) materials to enable a higher current carrying capability than conventional aluminium steel reinforced conductors. Depending on the conductor type used, thermal rating increases of 50-200% can be achieved without constructing new corridors. The technology is applicable to transmission, sub-transmission and distribution networks. It is maturing, with several HTLS conductors already at TRL 7–9.

Sample projects

National Grid Electricity Transmission in Great Britain has announced a large-scale programme of transmission upgrades using advanced conductors to increase network capacity while reducing the need for new routes, consents and associated civil works. In the US, utilities including Xcel Energy and Southern Company have begun deploying advanced conductors to increase transfer capacity on existing overhead line corridors. Across Europe, TSOs including Red Eléctrica, RTE and Terna have also deployed HTLS conductors in constrained areas of their networks to increase power transfer capability without building new overhead lines.

Advanced conductors are also attracting interest on distribution networks, particularly where reinforcement is needed quickly or where conventional civil works would be disruptive. Potential use cases include data centre connections, integration of distributed renewables, electrification-related load growth and capacity upgrades in congested urban networks.

Cost

Reconductoring costs vary depending on the voltage level, conductor type, outage requirements and any tower reinforcements required. Advanced reconductoring can often be less expensive than developing new transmission corridors, and so utilities are increasingly evaluating its feasibility before progressing with large-scale infrastructure expansion projects.

Timelines

The technology is commercially available and, where existing structures are suitable, can be delivered within a shorter timeframe than a new transmission corridor because it uses existing assets and rights of way. Growing electricity demand, renewable generation deployment, electrification and data centre deployment are driving increased interest in advanced conductor technologies.

Potential to scale

The potential to scale is significant, as advanced reconductoring offers a practical pathway to increase transfer capacity while minimising disruption, particularly in areas where reinforcement is urgently required or where new corridors are difficult to

develop. Reconductoring is increasingly being considered alongside dynamic line rating, topology optimisation and power flow control as part of a broader suite of grid-enhancing technologies.

ESB Activity

ESB Networks and EirGrid have experience of conductor replacement and uprating projects across the transmission network. ESB Networks is currently progressing a 38 kV uprating project at Ballyjamesduff with higher capacity conductors. ESB is monitoring developments in advanced conductor technologies internationally.

Leading Organisations

Leading technology providers include TS Conductor, CTC Global, Lamafil, Nexans, Prysmian, Apar Industries and Sterlite Power.

Summary

Advanced reconductoring is a mature technology that can significantly increase transmission capacity while reusing existing infrastructure and rights of way. While it will not remove the need for new transmission infrastructure, it is one of the most promising grid enhancing technologies available today. Combining advanced conductors with complementary solutions such as dynamic line rating and digital grid management systems may enable utilities to unlock additional network capacity, accelerate renewable integration and reduce congestion across existing transmission and distribution networks.

6 | The Electrification of (Almost) Everything

Electricity use is increasing, and its role in the energy system is expanding. There is an accelerating shift from fossil fuels to clean electricity across transport, heating and other uses. ESB's 'Driven to Make a Difference: Net Zero by 2040' strategy anticipates that electricity will become the dominant form of energy across most of Ireland's economy, including transport, heating/cooling, industry and digital infrastructure. The main exceptions are likely to be applications where direct electrification remains technically difficult or economically inefficient, such as long-haul aviation, shipping and high-temperature industrial processes.

This transition is now visible across almost every form of transport. Passenger EVs are increasingly mainstream, and commercial fleets and heavy goods vehicles are beginning to electrify. Rail systems are expanding battery and overhead-line solutions, while ports and ferries are adopting electric and hybrid vessels. Electric flight is progressing from prototypes towards early commercial uses. Heating is also changing rapidly, with reversible heat pumps, industrial heat pumps and district heating increasingly seen as central routes to decarbonising homes, buildings and industrial heat demand.

These electrification technologies will increase electricity demand, but they can also create new flexibility, reduce fossil fuel imports, improve air quality and support Ireland's pathway to a net zero energy system.

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6. The Electrification of (Almost) Everything (continued)

TRL
9

Battery Electric Heavy Goods Vehicles



Battery electric truck on the road (Credit: Daimler Truck AG)

Battery-electric heavy goods vehicles (HGVs) are emerging as a viable replacement for diesel engines in heavy road transport applications. Heavy transport has traditionally been considered difficult to electrify because of high energy demand, long duty cycles and payload requirements. However, advances in battery energy density, vehicle efficiency and high-power depot and public charging are making battery-electric solutions increasingly viable. Battery-electric HGVs are now commercially available for short, medium and some long-haul applications. Battery-electric HGVs are at TRL 9 for many depot-based and regional applications.

Sample projects

Battery-electric HGVs are now available from several major OEMs. Examples include the Mercedes-Benz eActros 600, which is designed for long-distance distribution and has a range of around 500 km, and the Tesla Semi, with a claimed range of 800 km.

Cost

Battery-electric HGVs currently have higher upfront capital costs than diesel trucks, but lower energy and maintenance costs can improve total cost of ownership, particularly for high-utilisation depot-based fleets with predictable routes. Depot charging is likely to be the lowest-cost route to early deployment, while public megawatt charging will be important for wider long-haul adoption.

Timelines

Lighter commercial vehicles and shorter-range HGVs are likely to electrify first, followed by heavier long-haul applications as battery costs fall and high-power charging becomes more widely available.

Potential to scale

The potential to scale is significant. China has already seen large-scale deployment of electric heavy-duty vehicles, indicating that rapid market growth is possible where vehicle supply, charging infrastructure and policy support align. Ireland may be comparatively well suited to battery-electric freight because distances are relatively short and many fleets operate from central depots. The key constraints will be vehicle availability, payload impacts, charging

downtime, depot grid connection capacity and the development of high-power charging infrastructure on strategic freight routes.

ESB Activity

ESB is monitoring the development of battery-electric heavy transport and the associated implications for electricity demand, public charging infrastructure and grid flexibility. Heavy transport electrification may create new demand growth opportunities, but it will also require careful planning of network capacity, charging locations and smart charging solutions.

Leading Organisations

Leading battery-electric HGV manufacturers include Volvo Trucks, Mercedes-Benz Trucks, Tesla and numerous Chinese manufacturers such as BYD and Sany.

Summary

Battery-electric heavy transport has advanced faster than many observers expected. Commercial HGVs now offer ranges that can meet a significant proportion of freight duty cycles. China has demonstrated that large scale deployment is possible. Battery-electric solutions are increasingly likely to become the dominant decarbonisation pathway for many heavy road freight applications. Hydrogen and other low-carbon fuels may still have a role in the most demanding long-haul, high-utilisation or infrastructure-constrained use cases, but the addressable market for direct electrification is expanding rapidly.

TRL 1-2	Concept phase / research	TRL 3-5	Small scale prototype deployed in lab / controlled environment	TRL 6-7	Large scale prototype or subsystems deployed in controlled environment	TRL 8	Large scale prototype deployed in commercial type environment	TRL 9	Mature technology, deployed at scale in commercial type environment
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TRL
9

Electric Rail Transport



Stadler battery electric train designed to operate on regional routes with non-electrified sections (Credit: Stadler)

Battery-electric rail transport uses onboard batteries to replace diesel traction on non-electrified or partially electrified rail routes. Rail is already highly electrified in many countries, but diesel locomotives remain in use on regional, rural and lower-density lines where full overhead electrification may be difficult to justify. Battery-electric multiple units can operate under overhead wires where available, recharge at terminals or short electrified sections, and use batteries to bridge unelectrified gaps. This makes the technology particularly relevant where operators want to decarbonise rail services without incurring the full cost and disruption of continuous route electrification. Battery-electric rail is commercially deployed in regional passenger applications and is at TRL 9 for selected use cases. Longer-range, heavy freight and high-utilisation applications remain more dependent on route-specific charging, infrastructure and operating requirements.

Sample projects

Battery-electric train projects are moving from demonstration to commercial deployment. Stadler's FLIRT Akku battery-electric unit is designed for regional routes with non-electrified sections. Hitachi is developing battery train solutions that can add flexibility to partial electrification strategies.

Battery-electric trains are being deployed across Europe, including on regional networks in Germany, Austria and Denmark. These projects show how battery trains can replace diesel locomotives on some lines while also continuing to use existing overhead electrification where available.

Cost

Battery-electric rail can avoid or defer the cost of full route electrification. The economics are strongest where battery range aligns with route length, waiting times allow recharging, and terminal charging can support reliable operation.

Timelines

Battery-electric rail is already entering commercial service on suitable regional passenger routes. Wider deployment is likely through the late 2020s and 2030s as rolling-stock procurement cycles turn over and battery performance improves. Heavy freight and long-distance intercity applications are likely to progress more slowly because of higher energy requirements and more demanding duty cycles.

Potential to scale

The potential to scale is significant on regional and branch-line passenger services, particularly where full overhead electrification is unlikely to be economic. Ireland has a very low share of electrified railway infrastructure compared with many European countries, so this may create opportunities for battery-electric rail on some routes.

ESB Activity

ESB is monitoring the development of battery-electric rail and its implications for electricity demand, grid connections and charging infrastructure.

Leading Organisations

Leading battery-electric rail suppliers include Stadler, Hitachi, Siemens, Alstom and CAF. These companies are developing battery-electric multiple units, hybrid battery trains and retrofit solutions for regional passenger rail markets.

Summary

Battery-electric rail provides a practical decarbonisation option for non-electrified and partially electrified rail routes, particularly regional passenger services where full overhead electrification may not be economic. The technology is commercially available and is increasingly being procured in Europe. Full electrification is still likely to remain preferable on high-frequency corridors. Hydrogen or other low-carbon fuels may retain a role where route lengths or infrastructure constraints make battery operation difficult.

6. The Electrification of (Almost) Everything (continued)

TRL
7-9

Improved EV Charging Technology



ESB electric vehicle at a charging point

EV charging technology is advancing from conventional fast charging towards higher-power and more flexible systems.

High-power DC charging is already used for fast charging across cars, vans and some fleets, typically at up to several hundred kilowatts. A Megawatt Charging System (MCS) is a newer standard designed mainly for heavy-duty vehicles, where much larger batteries and shorter charging windows are required.

The core technology is commercially available for high-power DC charging and battery-buffered systems, while MCS deployment remains at an early commercial stage and will depend heavily on grid connections, standards and vehicle compatibility. High-power DC charging is at TRL 9 and battery-buffered charging systems are at TRL 8. MCS-based charging is at TRL 7-8 as it moves from demonstration into early commercial deployment. Passenger EV charging will continue to improve through higher-voltage platforms, better battery thermal management and faster DC charging, but true MW-scale charging is initially likely to focus on larger vehicles.

Sample projects

In 2026, BYD installed a 1 MW Flash Charger in Paris (capable of adding 400 km of range after five minutes of charging). In 2026, a battery-buffered charging system in Regensburg, Germany, demonstrated how 300 kW charging could be delivered from a lower-capacity grid connection.

Cost

Megawatt-scale chargers and battery-buffered charging systems are capital intensive because they require high-power converters and advanced energy management systems.

Battery storage can also reduce demand charges and improve asset utilisation by allowing a smaller grid import capacity to support occasional high-power charging events. Fuel cells or temporary generators can also support charging where grid capacity is unavailable, but these options are likely to be more niche. They may be useful for construction sites or remote locations, but their operating costs must be assessed carefully.

Timelines

High-power DC charging is already commercial, while battery-buffered charging is entering wider deployment at fleet, public and constrained-grid sites. MCS is likely to scale through the late 2020s as vehicle and charger platforms and standards mature.

Potential to scale

The potential to scale is significant because charging speed, user experience and grid connection availability are becoming key considerations in the continued electrification of transport. Battery-buffered and managed charging solutions can increase the number of viable charging sites, especially where distribution networks are constrained or where grid upgrades have long lead times. The largest

opportunity is likely to be in commercial transport, where vehicle utilisation is high and charging downtime has a direct economic cost.

ESB Activity

ESB is evolving its charging solutions beyond public charger deployment towards a broader transport electrification platform spanning public, home and depot charging. Current activities include high-power charging, preparation for future MCS applications, Open Charge Point Interface-enabled roaming and interoperability, and smart charging solutions that can optimise constrained grid locations and integrate battery storage.

Leading Organisations

Leading suppliers in high-power and megawatt charging include ABB E-mobility, Kempower, Alpitronic, Siemens, Heliox, Ekoenergetyka and Tesla. Battery-buffered and grid-interactive charging solutions are being developed by a wider group of charging, storage and power electronics companies. These include firms integrating DC fast charging with on-site batteries, energy management software and renewable generation.

Summary

Improved EV charging technology is likely to become a key enabler of transport electrification. Megawatt-scale charging can support the electrification of heavy-duty vehicles, while battery and hybrid energy systems can help deliver high-power charging where grid capacity is constrained.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything	65
TRL 1-2 Concept phase / research	TRL 3-5 Small scale prototype deployed in lab / controlled environment	TRL 6-7 Large scale prototype or subsystems deployed in controlled environment	TRL 8 Large scale prototype deployed in commercial type environment	TRL 9 Mature technology, deployed at scale in commercial type environment			

TRL
6-9

Electric Flight



Heart Aerospace's electric aircraft in flight – the X1 demonstrator is the largest battery-electric aircraft ever flown (Credit: Heart Aerospace)

Electric flight uses battery and hybrid-electric propulsion in drones, small aircraft, eVTOL air taxis and short-range passenger aircraft. The technology is less mature than road or rail electrification because flight is highly sensitive to weight and battery energy density. Drones are already commercially mature in many applications and are at TRL 9. Small electric aircraft are entering early commercial use and are typically at TRL 8 for certain use cases.

Sample projects

In August 2026, Heart Aerospace completed a 27 minute test mission with a battery-electric regional-scale demonstrator aircraft at Plattsburgh International Airport in New York. The demonstrator was equivalent in size to a 30 seat aircraft. Joby Aviation and Archer Aviation are leading eVTOL developers pursuing certification, testing and initial urban air mobility services in the US. In China, EHang has begun offering short, bookable, autonomous sightseeing flights. Electric propulsion is already widely deployed in drones for inspection, surveying and deliveries.

Cost

Costs remain highly uncertain because most electric passenger aircraft and eVTOLs are in early certification and commercial development.

Drones are already economic in many inspection and monitoring applications because they avoid labour-intensive or hazardous manual work.

Timelines

Drones are already commercially deployed and will continue to expand as autonomy, sensors and regulations develop. Small electric training and specialist aircraft are entering early commercial use. eVTOL air taxis may begin limited commercial services in selected markets during the late 2020s, but widespread deployment will depend on certification, cost and public acceptance. Short-range regional electric and hybrid-electric aircraft are more likely to scale gradually through the 2030s. Full battery-electric large passenger aircraft are unlikely in the near term because of current battery energy density constraints and remain at a much lower maturity level than drones, eVTOLs or small aircraft.

Potential to scale

The potential to scale is strongest in drones, short-distance eVTOL routes and some regional passenger or cargo services. However, the technology's near-term impact will be modest because most aviation energy is used by larger aircraft on longer routes unsuitable for direct battery electrification. Sustainable aviation fuels, e-fuels and possibly hydrogen are likely to remain more important for medium- and long-haul aviation decarbonisation.

ESB Activity

ESB is already using and monitoring drone technologies for inspection and asset management across network and generation assets. Cyberhawk has supported ESB's Winter Resilience Programme through drone-based asset inspections and visual data management. ESB's eViation project is working alongside Future Mobility Campus Ireland, BETA Technologies and industry partners to assess the infrastructure and energy systems needed to support electric flight.

Leading Organisations

Leading companies include BETA Technologies, Heart Aerospace, Eviation, Joby Aviation, Archer Aviation, Vertical Aerospace, Airbus, Embraer/Eve, Pipistrel and AutoFlight. The diverse drone market includes manufacturers and service providers for inspection, mapping, logistics and autonomous infrastructure monitoring.

Summary

Electric flight is advancing, but its near-term impact will be concentrated in drones, specialist aircraft, air taxis and short-range regional services. Drones are already commercial, while small passenger aircraft and eVTOLs are moving through certification and early deployment. Battery energy density remains the main constraint for larger passenger aircraft, so electric flight is unlikely to materially decarbonise mainstream aviation in the near term.

6. The Electrification of (Almost) Everything (continued)

TRL
7-9

Electrification of Shipping



The world's largest battery-electric passenger ferry (Credit: INCAT)

Battery-electric shipping uses onboard batteries, high-efficiency electric propulsion and shore-based charging infrastructure to replace diesel propulsion in suitable maritime applications. The most mature use case is short-route ferry operations, where vessels operate on fixed routes, return regularly to the same ports and can recharge during scheduled turnaround periods. For longer-distance shipping, batteries are unlikely to replace energy-dense liquid fuels in the near term, because of their lower energy density compared with liquid fuels, but they can still reduce emissions through hybridisation, port operations, peak shaving and zero-emission manoeuvring.

The TRL is 9 for battery-electric ferries and harbour vessels on short, predictable routes and 7 for larger coastal vessels. Deep-sea battery-electric shipping remains constrained by battery energy density and charging requirements.

Sample projects

In Norway, the world's first fully electric car and passenger ferry (the MF Ampere) has been operating for over 10 years. Norway currently has more than 100 electric car and passenger ferries in service. In 2026, a fully electric ferry measuring 130 m that can carry 2,100 passengers and 225 vehicles was built in Australia. It is intended to operate on a 60 km route in South America and will require a 40 minute recharge at each port.

Cost

Capital costs are generally higher than for conventional diesel vessels because of battery systems, charging infrastructure and grid connection costs, but operating costs can be lower where electricity prices are favourable and the vessels have high utilisation.

Timelines

Battery-electric ferries are already commercial and are likely to continue scaling across Europe through the late 2020s and 2030s. Studies suggest that more than half of existing EU ferries could technically rely on battery-electric propulsion by 2035, with a significant subset already cost-competitive or approaching cost competitiveness.

Potential to scale

The potential to scale is strongest in ferries, harbour craft, offshore support vessels, and inland waterway vessels with predictable schedules and available port grid capacity.

ESB Activity

ESB is monitoring transport electrification and the associated implications for electricity demand, grid connections, smart charging and customer-side flexibility.

ESB is working with Rosslare Europort as a real-world testbed to explore port electrification, energy sharing, flexibility services and transport-energy hubs. This will help shape how large energy users connect and operate within the future electricity system.

Leading Organisations

Electric shipbuilders include Candela and Incat. Marine battery, propulsion, charging and control-system suppliers include ABB, Siemens, Wärtsilä, Kongsberg, Danfoss Editron, Leclanché and Echandia.

Summary

Battery-electric shipping is commercially proven for ferries and other short-route vessels and is likely to be one of the most efficient ways to decarbonise these maritime operations. The technology is less relevant to deep-sea shipping, where sustainable liquid fuels such as ammonia, e-fuels or biofuels may be required.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything	67
TRL 1-2 Concept phase / research	TRL 3-5 Small scale prototype deployed in lab / controlled environment	TRL 6-7 Large scale prototype or subsystems deployed in controlled environment	TRL 8 Large scale prototype deployed in commercial type environment	TRL 9 Mature technology, deployed at scale in commercial type environment			

TRL
9

Reversible Heat Pumps



Reversible heat pumps (Credit: Kristoferb, Wikimedia Commons, CC BY-SA 3.0)

Reversible heat pumps are electrically driven systems that can provide both heating and cooling by reversing the direction of the refrigeration cycle. In heating mode, they extract low temperature heat from air, ground or water and upgrade it for space heating or domestic hot water. In cooling mode, the cycle is reversed, enabling the same equipment to operate as a cooling system. This dual functionality makes reversible heat pumps particularly relevant for buildings that require both winter heating and summer cooling.

The technology itself is commercially mature at TRL 9. Its wider application in Ireland remains an emerging opportunity, particularly where electrification, cooling demand and demand-side flexibility can be combined.

Sample projects

Reversible heat pumps are already widely deployed across Europe, particularly in regions where buildings or district-energy networks require both heating and cooling. In Scandinavia and Central Europe, large reversible heat pumps in the 5–50 MW range have been deployed in district energy systems to provide seasonal heating and cooling. Commercial buildings in France, Germany and the Netherlands are also adopting reversible air-to-water systems to meet both heating and cooling loads with one technology platform.

Cost

Reversible heat pumps generally have a higher upfront cost than heating-only heat pumps. This reflects the additional valves, controls and heat exchanger complexity required to provide both heating and cooling. A CAPEX premium of around 10–20% is commonly cited, although actual costs vary significantly by building and system type.

Timelines

Small reversible heat pumps are already widely deployed across Europe in residential and commercial buildings. In Ireland, the timeline issue is not about the technology but rather about the pace of adoption. Deployment could accelerate during the late 2020s as building electrification, cooling requirements and energy-performance standards become stronger drivers for commercial and public-sector buildings.

Potential to scale

Reversible heat pumps have strong long-term scaling potential as heating and cooling increasingly become part of an integrated electrified energy system in a warming world.

ESB Activity

ESB is monitoring reversible heat-pump technologies as part of its broader interest in electrification, customer decarbonisation and demand-side flexibility. The technology may become relevant where it can support electrified heat, cooling services and flexible electricity demand in commercial or district-energy applications.

Leading Organisations

Leading organisations in this area include Daikin, Siemens and Bosch.

Summary

Reversible heat pumps are a mature and increasingly important technology for the electrification of heating and cooling. Their ability to provide both services from a single asset can improve utilisation and support lower-carbon building operation. In Ireland, their strategic value is likely to increase as cooling demand grows and as heat electrification develops. While the technology is already commercially proven, its wider impact will depend on integration with suitable buildings, waste-heat sources and flexibility markets. In this context, reversible heat pumps could play a useful role in linking heating, cooling and grid flexibility within Ireland's future energy system.

6. The Electrification of (Almost) Everything (continued)

TRL
9

Industrial Heat Pumps



Industrial heat pump system (Credit: Turboden Sp.A, a Group Company of Mitsubishi Heavy Industries)

Industrial Heat Pumps (IHPs) are heat pumps used in an industrial setting that actively recover waste heat and can provide temperatures of up to 200°C. The TRL of IHPs varies according to the temperature output. According to the IEA's Technology Collaboration Programme (TCP) on High Temperature Heat Pump (HTHP), IHPs achieving temperatures of 120°C are at TRL 9. IHPs achieving temperatures of 160°C and above are expected to become commercial in the near future. Higher temperatures of up to 200°C can be achieved more efficiently with the addition of Mechanical Vapour Recompression (MVR - TRL 9) to an IHP.

Sample projects

The Irish company Astatine has successfully installed a 1 MW IHP, supplying temperatures of 120°C, at the Ahascragh Distillery, Co. Galway.

In Esbjerg, Denmark, the world's largest CO₂ based seawater heat pump started operation in November 2024. The 70 MW heat pump supplies 25,000 customers through the local District Heating Network.

Cost

With higher Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), IHPs can struggle to compete economically with gas-fuelled alternatives. However, costs are highly application-specific and improve where high-quality waste heat sources, high utilisation, carbon costs, process cooling co-benefits or targeted grant support are available. EU and national funding streams are increasingly being directed at industrial heat pump and district-heating decarbonisation projects.

Timelines

The rollout of IHPs is gaining momentum, and Ireland's 2024 Climate Action Plan includes an action to deliver a roadmap to phase out fossil fuels for all heat uses under 140°C.

Potential to scale

IHPs have the potential to replace all fossil fuel heating solutions under 200°C. Currently, the higher electricity costs and CAPEX relative to natural gas installations are barriers to the rollout of IHPs and result in a requirement for grant support to enable adoption. The principal support system for IHPs is the Support Scheme for Renewable Heat, which offers CAPEX grants of up to 40% or €1 million depending on the temperature output and the system's coefficient of performance.

ESB Activity

ESB delivered an 870 kW ammonia heat pump with 65°C water output for one of Europe's leading food processors, ABP Food Group. ESB has deployed heat pumps in the UK at two large greenhouses in East Anglia. The total thermal output is 72 MWth and the total area of the greenhouses is 29 hectares.

Leading Organisations

Leading IHP OEMs and technology providers include Everllence, GEA, Johnson Controls, Mayekawa and Ochsner, while Heaten, Futraheat and AtmosZero are emerging specialists. Everllence offers hot water and steam-generating heat pump solutions delivering water and steam temperatures up to 150°C and above when in a cascade configuration. Newer entrants are targeting modular steam and process-heat applications up to around 200°C.

Summary

The outlook for IHPs in Ireland is positive, particularly in sectors such as food and beverage where there is strong demand for low- and medium-temperature process heat. IHPs are increasingly capable of supplying these temperature ranges, especially where suitable waste-heat sources are available. However, wider adoption will depend on project-specific economics, including electricity-to-gas price ratios, upfront capital costs and the availability of grant support.

Overview	Low Carbon Generation	Energy Storage	The Empowered Customer	CCUS	Grid Technologies	The Electrification of (Almost) Everything
TRL 1-2 Concept phase / research	TRL 3-5 Small scale prototype deployed in lab / controlled environment	TRL 6-7 Large scale prototype or subsystems deployed in controlled environment	TRL 8 Large scale prototype deployed in commercial type environment	TRL 9 Mature technology, deployed at scale in commercial type environment		

TRL
8-9

Novel Forms of District Heating



District heating pipes ready to be laid in Germany

District Heating (DH) uses one or more energy centres to distribute heat to residential, industrial and commercial premises through insulated hot-water pipes (third generation). Fourth-generation district heating (4GDH, TRL 9) uses low-temperature water and integrates renewable energy sources. Fifth-generation District Heating (5GDH, TRL 8) systems use ambient temperature networks with decentralised heat sources.

District heating can use a wide range of heat sources, including waste heat recovery, solar thermal, geothermal energy and heat pumps. Thermal storage can also be integrated to support peak shaving and demand response.

Sample projects

The Tallaght 4GDH Scheme can supply up to 3 MW of heat to public buildings by using two heat pumps to upgrade waste heat from a nearby data centre. Fortum designed and built the network and is responsible for its operation and maintenance. A planned expansion could connect residential buildings once network and market regulations for district heating are established.

Cost

DH costs vary substantially but are generally lower in areas with higher heat-demand density. A 2024 Irish District Energy Association report estimated a Levelised Cost of Heat of €93/MWh for a data centre waste-heat scheme in a high-density area, comparable to the cost of individual air-source heat pumps. In 2025, DCEE allocated €5 million from the Climate Action Fund to district-heating development costs through the Pre-Construction Fund. A further €50–100 million from the Infrastructure, Climate and Nature Fund was also allocated to support construction of district heating projects.

Timelines

The 2024 Climate Action Plan sets out a target of 2.7 TWh of DH to be delivered by 2030. Dublin City Council is preparing a joint-venture procurement to deliver and operate the Dublin District Heating Project (DDHP), using up to 90 MW of waste heat from the Dublin Waste to Energy facility, with a back-up boiler. DCEE has allocated €50 million from the Climate Action Fund for the DDHP.

Potential to scale

There is very little DH in Ireland today. However, in other jurisdictions (notably the Nordic and Eastern European countries), DH has reached penetration levels of 50-90% of heat supply. The National Heat Study found that up to 54% of residential and SME heat demand in Ireland could be met through DH. The density of heat

demand is one of the deciding factors when scaling DH networks. A spatial analysis from SEAI, prioritising the highest heat density areas, found that of the 2.7 TWh target set out in the current Climate Action Plan, 50% could be delivered in Dublin and Cork cities alone.

ESB Activity

ESB is actively monitoring the development of DH in Ireland, particularly where district heating intersects with heat electrification, large-scale heat pumps, waste heat recovery and thermal storage.

Leading Organisations

Utilities, local authorities, energy service companies and specialist operators typically develop and operate DH networks. In Europe, leading companies with Irish operations include Veolia and Fortum.

Summary

District heating currently provides less than 1% of Ireland's heat demand, placing Ireland among the lowest users of district heating in the EU. However, successive Climate Action Plans recognise its potential role in decarbonising heat, particularly in dense urban areas and locations with access to waste heat. A clear regulatory framework, targeted financial support and coordinated local planning will be critical to scaling district heating in Ireland.

Glossary of Acronyms

Acronym	Meaning
AC	Alternating Current
AD	Anaerobic Digestion
AEM	Anion Exchange Membrane
AGS	Advanced Geothermal Systems
AI	Artificial Intelligence
AR	Allocation Round
BECCS	Bioenergy Carbon Capture and Storage
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCS2	Combined Charging System Type 2
CCUS	Carbon Capture, Utilisation and Storage
CfD	Contracts for Difference
CHP	Combined Heat and Power
CIGRE	International Council on Large Electric Systems
CO ₂	Carbon Dioxide
DAC	Direct Air Capture
DC	Direct Current
DCEE	Department of Climate, Energy and the Environment
DH	District Heating
DLR	Dynamic Line Rating
DNV	Det Norske Veritas
EGS	Enhanced Geothermal Systems
EMEC	European Marine Energy Centre
EPRI	Electric Power Research Institute

Acronym	Meaning
ETS	Emissions Trading Scheme
EV	Electric Vehicle
eVTOL	Electric Vertical Take-Off and Landing
FLOW	Floating Offshore Wind
GIS	Gas Insulated Switchgear
GW	Gigawatt
GWh	Gigawatt-hour
HEFA	Hydro-processed Esters and Fatty Acids
HGV	Heavy Goods Vehicle
HTHP	High Temperature Heat Pump
HTLS	High Temperature Low Sag
HV	High Voltage
HVDC	High Voltage Direct Current
HVO	Hydrotreated Vegetable Oil
IEA	International Energy Agency
IHP	Industrial Heat Pumps
IRENA	International Renewable Energy Agency
LAES	Liquid Air Energy Storage
LDES	Long Duration Energy Storage
Li-ion	Lithium-ion
LV	Low Voltage
MCS	Megawatt Charging System
MoU	Memorandum of Understanding
MV	Medium Voltage
MVDC	Medium Voltage Direct Current

Acronym	Meaning
MVR	Mechanical Vapour Recompression
MW	Megawatt
MWe	Megawatt electrical
MWh	Megawatt-hour
MWth	Megawatt thermal
Na-ion	Sodium-ion
O&M	Operations and Maintenance
ODOW	Other Deepwater Offshore Wind
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
ORC	Organic Rankine Cycle
PPA	Power Purchase Agreement
PUE	Power Usage Effectiveness
PV	Photovoltaic
RD&D	Research, Development and Demonstration
RWGS	Reverse Water Gas Shift
SAF	Sustainable Aviation Fuel
SEAI	Sustainable Energy Authority of Ireland
SF ₆	Sulphur Hexafluoride
SMR	Small Modular Reactor
SOEC	Solid Oxide Electrolyser Cell
SONI	System Operator for Northern Ireland
SST	Solid-State Transformer
TES	Thermal Energy Storage
TRL	Technology Readiness Level

Acronym	Meaning
TSO	Transmission System Operator
TWh	Terawatt-hour
UPS	Uninterruptible Power Supply
V2G	Vehicle-to-Grid
V2X	Vehicle-to-Everything
VFB	Vanadium Flow Battery
WEC	Wave Energy Converter



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