Energy for generations

Emerging Technology Insights 2025

ESB Innovation

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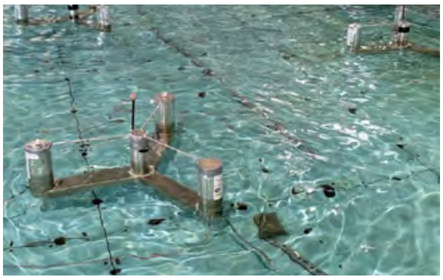
Executive Summary

ESB's strategy 'Driven to Make a Difference: Net Zero by 2040' commits ESB to net zero carbon emissions by 2040. Established technologies, such as wind energy (onshore and offshore), solar PV and Li-ion batteries will be critical to achieving a net zero energy system, but we will also need to use additional emerging technologies.

Our view of the leading emerging technologies for each category in this report are given below and they will require financial and policy support to achieve their potential.



Generation
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High Voltage Direct Current (HVDC) transmission (p. 44)

Great progress is being made with these emerging technologies. The following is a list of key projects that have been completed or successfully demonstrated in the last year across Europe.

Polar Night, Finland 100-hour thermal storage

Seaturns, France 1:4 scale wave energy device deployed

EDF and Partners, France 25 MW floating wind farm, featuring tension leg platforms

Equinor, Norway 'Northern Lights' Carbon Capture and Storage (CCS)

Eni-Snam, Italy Ravenna CCS

Energy Dome, Italy 20 MW 'CO_2 battery' plant

Supernode, UK 30 metre superconducting cable demonstration

Migaldi, Italy 7.5 MWh 'green steam' thermal storage plant

INERATEC, Germany efuel plant in Frankfurt

Octopus/BYD, UK - Launch of UK's first vehicle-to-grid (V2G) bundle

Beyond Europe, the following projects have been completed in the last year.

Envision, China The world's largest green hydrogen and ammonia plant is now operational

Proteus Marine Renewables, Japan 1.1MW 'AR1100' tidal turbine deployed

CATL, China Na-Ion battery under the 'Naxtra' brand launched – this is the world's first mass produced Na-Ion battery

Overview

Purpose

This report provides an update on emerging energy technologies in Ireland and ESB's interactions with these technologies. The report aims to stimulate discussion, collaboration and innovation.

Scope

This report objectively reviews emerging energy technologies. Established and commercially mature technologies, such as onshore wind or Li-ion batteries, are not emerging and therefore not considered in scope.

Emerging technologies are principally evaluated using the Technology Readiness Level (TRL) scale and their estimated time to commercialisation.

Commercialisation

Time to commercialisation and costs are estimated for the Ireland and UK markets. Prices quoted are from publicly available sources and are illustrative only.

Technology Readiness Level (TRL)

An overview of the status of all technologies in terms of their Technology Readiness Level and their commerciality

- **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

5-10 years to Commerciality | 1-5 years to Commerciality | Commercial / Early Commercialisation | TRL progress in 2024

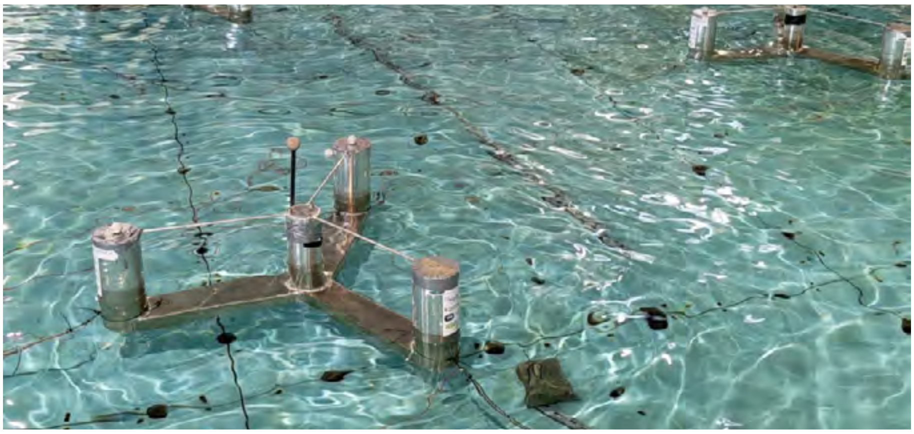
TLR	Generation	Storage	Empowered Customer	Carbon Capture Utilisation and Storage (CCUS)	Grid Technologies
TLR 9	Floating Offshore Wind	Sodium-Ion Battery Storage Bio-Derived Renewable Diesel Flow Battery Storage Thermal Energy Storage Hydrogen Storage (Large Scale) E-Fuels	Industrial Heat Pump Vehicle to Everything Charging District Heating (4th and 5th Generation) Anaerobic Digestion & Biomethane	Nature Based Solutions Bioenergy Carbon Capture and Storage Biochar Point Source Carbon Capture	High Voltage Direct Current Transmission Static Synchronous Compensator (STATCOM)
TLR 8	Tidal Stream Energy Geothermal Energy (Next Generation) Power Generation from Renewable Hydrogen	CO_2 Battery Storage		Direct Air Capture	SF_6 Free Equipment
TLR 7	Wave Energy Airborne Wind	Advanced Compressed Air Energy Storage Iron-Air Batteries			
TLR 6	Small Modular Reactors				
TLR 5					High Temperature Superconductor Cables
TLR 4	Nuclear Fusion				

1. Generation

1. Generation (continued)

TRL
9

Floating Offshore Wind



Floating Wind research project in the Lir Centre, UCC (Credit. UCC)

Floating Offshore Wind (FLOW) energy consists of wind turbines mounted on floating structures attached to the seabed using various mooring arrangements. There is a wide variety of platform designs. Some are more mature and developed than others. Leading consultant, DNV, reports floating wind at TRL 9 for leading technologies.

Sample project

Provence Grand Large is a 25 MW pilot project, 17 kilometres off the south coast of France, near Marseille. It features 3 x 8 MW turbines installed on tension leg platforms. It was commissioned in Q2 2025.

Cost

The UK Contracts for Difference (CfD) allocation round (AR7) strike price for FLOW has been set at £271/MWh (2024 prices). Floating wind has its own auction pot (Pot 4) and will receive 20-year contracts, up from 15 years in previous allocation rounds.

Timelines

In Ireland, FLOW is in the post-2035 timeline. In Great Britain, significant projects such as Kincardine and Hywind have already been developed. Norway also has deployed a floating wind project to power oil and gas fields (Hywind Tampen). In France, the 25 MW Provence Grand Large wind farm was recently completed.

Potential to scale

FLOW has great potential to scale in Ireland, particularly off the south and west coasts, with at least 30 GW potentially available.

ESB Activity

ESB has a number of FLOW projects under development. These include:

- The 500 MW Stoura project off Shetland's east coast.
- An innovative 100 MW project – Malin Sea Wind – in the Malin Sea.
- ESB, with EDF Renewables UK and Reventus Power, 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 north west 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 (DCEE) on plans for a floating demonstrator project.
- ESB has invested in Dublin Offshore, developers of novel floating offshore wind mooring technology.
- ESB is collaborating with University College Cork (UCC) on a 'wet storage' research project.

Leading OEMs

Leading OEMs (by installed capacity) include Principal Power for semi-submersible platforms and Equinor for spar platforms.

Summary

FLOW has a positive outlook in Ireland, with very large potential for significant scaling. Ireland's energetic sea states may pose technical and cost challenges. However, the average significant wave heights off Ireland's south coast are roughly equivalent to conditions in the seas off Brittany, where successful recent auctions for floating wind have taken place.

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

Wave Energy

Wave energy converter, deployed in Portugal (Credit. CorPower Ocean)

The motion of surface ocean waves contains significant amounts of kinetic energy that can be captured by Wave Energy Converters (WEC). The energy is converted to electricity through power take-off systems by pitch, heave or surge responses to incident waves. Wave energy is at TRL 6 to 7, with some full-scale demonstrations underway.

Sample project

CorPower Ocean deployed a full-scale prototype off the Portuguese coast in late 2023. It successfully exported power to the grid and survived several major storms.

Cost

The UK Allocation Round 7 (AR7) published in July 2025 has an administrative strike price for wave energy of £386 in 2024 prices. To date, no wave energy project has been successful in UK allocation rounds. Without a ring fenced budget similar to that in AR6 for tidal stream, it will be challenging for wave energy to be competitive.

Timelines

The EU Green Deal set a target of 100 MW of Ocean Energy (Wave + Tidal) to be deployed by 2027 and 1 GW by 2030. In addition, Portugal has a national wave energy target of 200MW of installed capacity by 2030. According to Ocean Energy Europe, less than 1 MW of wave energy is currently in the water in Europe.

Potential to scale

Ireland has some of the best wave resources in the world, with the potential up to 19GW according to the Evolve project. The SEAI Offshore Renewable Energy Technology Roadmap 2040 significant wave energy scenario has 4GW deployed by 2050. Significant technology development and price drops driven by volume and cycles of learning similar to historic developments for wind and solar will be required for wave energy to be deployed at scale. Enabling infrastructure, such as timely permitting processes for sites including test sites and grid connections, will also be needed to achieve scale.

ESB Activity

ESB developed the Saoirse Wave Energy project in collaboration with CorPower Ocean. This is a 4.9 MW wave farm pilot that secured €39.5m from the EU Innovation Fund and was initially to be developed off the coast of County Clare. However, despite significant progress, the development timeline has been pushed outside the time limit set by the Innovation Fund grant agreement. The project now plans to move to another site in Europe to allow the project objectives to be delivered on plan.

Leading OEMs

CorPower Ocean is leading the offshore wave energy technology development. It has a full-scale prototype deployment in Portugal and a pipeline of projects with secured grant support. French developer Seaturns is also making significant progress with its technology development. It has completed a 1:4 scale demonstration and is aiming to demonstrate a full-scale prototype in late 2025. EcoWave Power is leading the development of shore-mounted WECs, with the first US wave array under construction in Los Angeles.

Summary

After decades of high failure rates in technology development, wave energy demonstrations are now progressing across a number of technologies in a number of European countries. Technology developers are attracting public and private funding. The leading projects are addressing some of the fundamental challenges to make wave energy a mainstream energy source including storm survivability and structural efficiency. These challenges including scalability are critical to unlocking its potential.

1. Generation (continued)

TRL 8

Tidal Stream Energy

Tidal energy converter, deployed in Scotland (Credit. Magallanes Renovables)

Tidal Energy Converters harness the kinetic energy of horizontal tidal water flow to power turbines. The three principal technology types are: seabed mounted turbines, floating turbines and tidal kites. The International Renewable Energy Agency (IRENA) report Tidal Stream at TRL 8 for leading technologies.

Sample projects

- In 2019, Magallanes installed the 1.5 MW floating tidal turbine, 'ATIR', at the European Marine Energy Centre (EMEC) in Orkney, Scotland.
- In August 2021, Orbital Marine Power's O2 turbine (2 MW) started grid-connected power generation at EMEC.
- In Q1 2024, the Minesto 1.2 MW Tidal kite started grid-connected power generation in the Faroe Islands.
- In Q1 2025, Proteus Marine Renewables deployed the 1.1 MW 'AR1100' tidal turbine in Japan to deliver power to the Goto Islands.

Cost

The UK Allocation Round 7 published in July 2025 has an administrative strike price for tidal energy of £371 in 2024 prices.

Timelines

Tidal energy is at an early commercial stage in the UK where the industry is targeting 1 GW of deployments by 2035.

Potential to scale

In the Republic of Ireland, the potential to scale with existing technology is low due to a lack of high resource sites. In Northern Ireland, there is better resource potential with the opportunity for hundreds of MWs of tidal energy, but the required Marine Planning policies are not in place. The UK and France each have the potential to achieve a >1 GW scale pre-2040 and multiple GWs post-2040. Outside Europe, Canada and Japan are important markets with high scaling potential.

ESB Activity

ESB is maintaining a watching brief on tidal energy.

Leading OEMs

Leading OEMs include Magallanes Renovables and Orbital Marine Power (floating), SIMEC Atlantis EnergySAE and Proteus Marine Renewables (seabed mounted), and Minesto (tidal kites).

Summary

The outlook in the Republic of Ireland is challenging as there are no sites suitable for utility scale development using existing technology. In Northern Ireland, the outlook is more mixed as suitable sites exist off the Antrim coast, but the route to market and grid connection solutions remains unclear. In Britain, the outlook is positive with a clear route to market and numerous suitable sites.

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

Geothermal Energy (Next Generation)

Eavor project in Geretsried, Germany (Credit. Eavor)

Geothermal energy is thermal energy derived from 'hot rocks' within the earth's sub-surface. Geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean, consistent electricity.

Geothermal systems are broadly categorised as 'conventional' or 'next generation'.

In conventional geothermal systems, fluids circulate through simple bore holes or naturally occurring fissures.

Next generation geothermal includes Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS). In EGS, fluids circulate through engineered fissures. AGS are closed loop systems that function as large heat exchangers. Leading next generation geothermal technologies are at TRL 7-8.

Sample projects

- In July 2023, US based Fervo announced the successful full-scale test of its Nevada 3.5 MW EGS test plant called Project Red.
- Canadian startup Eavor has operated an AGS demonstration project since 2019 in Alberta province. It is also developing a larger project in Gerestried in Germany. The plant aims to deliver 65 MW of thermal energy and 8 MW of electrical energy on completion in 2027.

Cost

Geothermal energy costs vary hugely depending on location and technologies. The Eavor AGS project in Germany will receive a fixed power price of €227/MWh until 2042. This project received a €91.6 million grant from the European Innovation Fund.

Geothermal is attracting capital in the US. For example, Fervo raised $206 million in Q2 2025 to progress a 100 MW project in Utah.

Timelines

A number of demonstrators are now in place for next generation geothermal plants. The Fervo Utah project phase 1 (100 MW) is planned for 2026, with phase 2 (400 MW) planned for 2028.

Potential to scale

One attractive feature of next generation geothermal is that is can be sited, in theory, almost anywhere. The potential to scale is enormous if the technology progresses and the costs drop.

ESB Activity

ESB is keeping a watching brief on next generation geothermal.

Leading OEMs

Eavor, Fervo Energy and Sage Geosystems.

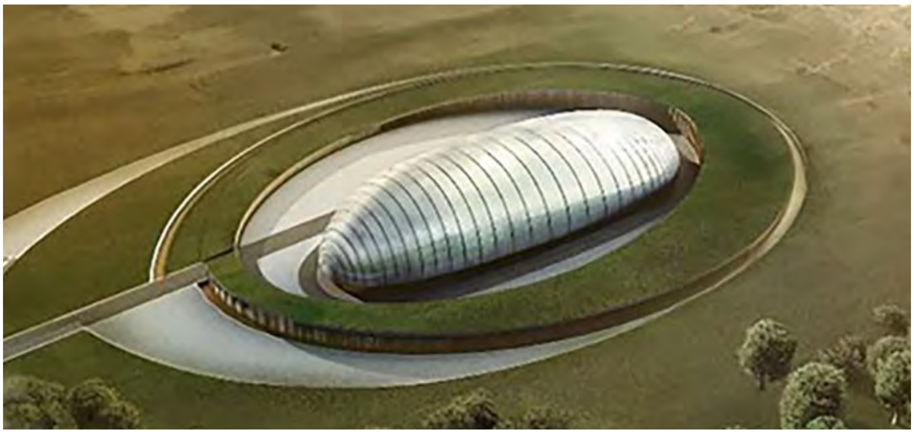
Summary

The global outlook for next generation geothermal is positive. In Ireland, which has comparatively low geothermal resources, the outlook is less positive. However, there is potential for deployment if the technology develops further and prices decrease.

1. Generation (continued)

TRL
6-7

Small Modular Reactors



Graphic of planned SMR. Image courtesy of Rolls Royce and the BBC

Small Modular Reactors (SMRs) are advanced nuclear reactors that have a power capacity of between 20 MW_e and 400 MW_e per unit. The small modular design enables multiple uses including electricity production for the grid and generating electricity and heat for industrial applications. The waste heat can also be recovered for district heating. The concept is still at an early stage (TRL 6) with more than 80 commercial SMR designs currently in development in over 19 countries. These are using a variety of designs including Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR) which are based on conventional nuclear power. Designs for an Advanced Modular Reactor (AMR) are still emerging.

Sample projects

- In Hainan Island, China, the construction of a 125Me PWR prototype ACP100 started in July 2021 and is scheduled for completion in 2026. This reactor, known as Linglong 1, is expected to be the world's first commercial SMR once it is commissioned in 2026.
- The CAREM-25 project in Argentina is due to be commissioned in the late 2020s and is currently undergoing some engineering revisions.

Cost

The costs of SMRs are subject to high degree of uncertainty due to the lack of published demonstration projects. The Bloomberg New Energy Finance (BNEF) LCOE benchmark for SMRs in the second half of 2024 was $421/MWh. There is also a high level of uncertainty about the costs of certifying new designs and construction costs for new factories.

Timelines

The first SMRs are expected to be built this decade, followed by accelerated deployment in the 2030s.

Potential to scale

Globally, SMRs have attracted a lot of interest as a source of zero carbon electricity. The technology has the potential to scale to deliver large volumes of zero carbon electricity.

ESB Activity

ESB has no direct involvement in SMRs but is keeping a watching brief. The production of electricity for the Irish national grid by nuclear fission is prohibited in the Republic of Ireland by the Electricity Regulation Act, 1999 (Section 18).

Leading OEMs

NuScale Power, CNNC, TerraPower, Westinghouse Electric, Nuward (EDF), GE Hitachi, Holtec International, Rolls-Royce, X-Energy.

Summary

Globally SMRs hold the promise of zero carbon dispatchable energy and could play a crucial role in providing reliable, firm and low carbon energy. They have attracted a lot of investment and attention; however, the concept and technology currently remain unproven due to a lack of demonstration 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 8

Power Generation from Renewable Hydrogen

ESB Hydrogen Fuel Cell

Hydrogen can be used as a fuel to generate electricity. Hydrogen derived from renewable energy sources via electrolysis is classified as 'renewable hydrogen'. Focusing on the turbine technology (and not the entire project infrastructure), the TRL can be defined at 7-9, depending on the blend of hydrogen and the scale of the system. Another method to combust renewable hydrogen is by using a reciprocating engine, and this is already at TRL 9.

Hydrogen can also be converted into electricity using fuel cells, which combine oxygen from the air and hydrogen to produce power and water. Hydrogen fuel cells are currently at TRL 9.

Sample project

In 2023, the Hyflexpower pilot project in France delivered the world's first successful demonstration of an integrated industrial electricity-to-hydrogen-to-electricity solution using 100% renewable hydrogen to generate zero carbon electricity. The turbine manufacturers were Siemens Energy and the output of the system was 12 MW. The same OEM has recently announced its plans to develop a 600 MW turbine capable of burning 100% hydrogen.

Cost

In late 2024, three hydrogen production Contracts for Difference were signed in the UK under the first Hydrogen Allocation Round (HAR1) for renewable hydrogen projects. The average strike price was £9.49/kg.

Timelines

GE and Siemens Energy have both pledged to make all their new turbines capable of burning 100% hydrogen by 2030. The development of utility scale projects that would include renewable hydrogen production, storage, transportation, and combustion of 100% hydrogen is expected to occur post-2035.

Potential to scale

Given Ireland's offshore wind ambition there is a very large potential to scale. Renewable hydrogen could enable the storage of terawatt hours (TWh) of energy in Ireland, providing a seasonal storage solution.

ESB Activity

ESB is developing a number of projects for power generation from hydrogen. An example is the HyNet project in Northwest England, which will use hydrogen as part of the fuel blend in the Carrington power station.

ESB has been actively demonstrating the use case for green hydrogen with our two hydrogen power units which produce electrical power from hydrogen gas. As part of the use case, we have collaborated with external partners to demonstrate the end use of hydrogen as a clean source of fuel and through this have developed our own internal capability and experience in relation to hydrogen to power. In addition, a 1MW electrolyser and hydrogen production facility is due to be built at ESB's power station in Aghada, Cork in 2026.

Leading OEMs

Siemens, Mitsubishi, and GE are three of the leading turbine OEMs.

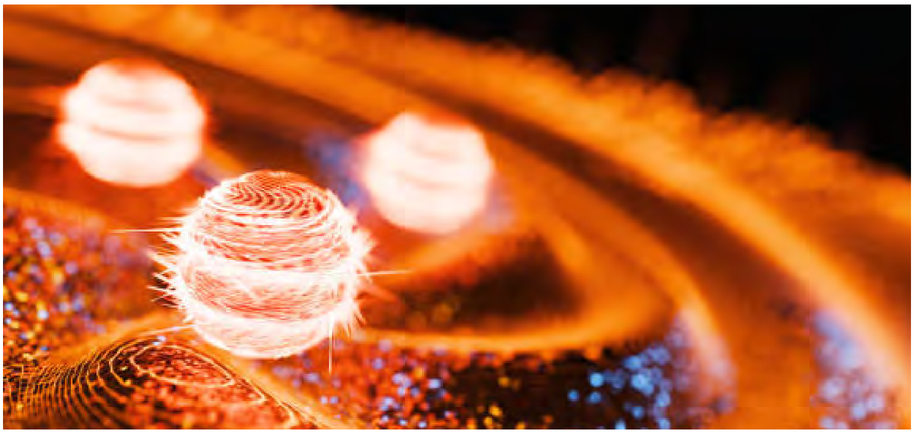
Summary

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

1. Generation (continued)

TRL
3-5

Nuclear Fusion



Nuclear fusion (3D-generated image)

Unlike nuclear fission (used in existing nuclear power plants) where atoms are split to release energy, nuclear fusion involves bringing light atomic nuclei together to release energy. Fusion is the process that produces energy in our sun and 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) which is a challenge to achieve and maintain. Leading nuclear fusion technologies are at TRL 4.

Sample projects

- Helion Energy's Polaris system is making progress and is being prepared to generate electricity: Helion has agreed a power purchase agreement 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 scheduled for 2030. CFS plans to build a 400 MW grid-scale fusion power plant in Virginia in the 2030s.
- In January 2025, China's Experimental Advanced Superconducting Tokamak (EAST) nuclear fusion reactor achieved a groundbreaking milestone in nuclear fusion research by sustaining plasma for 1,066 seconds. However, they're still working on how to turn the energy generated into usable electricity.

Cost

For fusion to be cost competitive with other forms of energy generation its capital costs need to be significantly reduced. There are several companies which are commercialising fusion power generation and planning to reduce its cost through innovative designs of the magnetic containment field. Fusion has been successful in raising funds recently. For example, CFS has raised $863m in its series B2 financing. In Europe, the largest investment has been in Proxima Fusion, which raised €130m in a series A financing round. In addition, Google and Microsoft have signed offtake agreements with CFS and Helion, respectively.

Timelines

Without further milestone technical breakthroughs, nuclear fusion is at least a decade away from commercial viability.

Potential to scale

Nuclear fusion offers the potential for clean and virtually limitless electricity generation.

ESB Activity

ESB has no direct involvement in nuclear fusion. However it's a technology we actively track.

Leading OEMs

Commonwealth Fusion Systems, TAE Technologies, Helion Energy, General Fusion, Neo Fusion, Zap Energy, Tokamak Energy, First Light Fusion, Kyoto Engineering, Focused Energy, Proxima Fusion.

Summary

Nuclear fusion holds the promise of a clean and plentiful energy source. However, to become commercially viable it will need to overcome several significant engineering and financial challenges. Significant public and private investment are being used to make this a reality. However, it remains at least a decade away unless there is a technology breakthrough.

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

Airborne Wind

Kitepower in Klixbull, Germany (Credit. Skysails)

Airborne Wind Energy Systems (AWES) are towerless wind turbines, generally either aircraft or kite-type devices, which are tethered to the ground or to a portable station. AWES are designed to be flown at altitudes of several hundred metres to harness higher wind speeds. AWES sizes vary, but as a representative example, the SkySails Venyo (PN-14) system has an externally verified power curve at 120 kW. National Renewable Energy Laboratory (NREL) have reported the leading technology types at TRL 7.

Sample projects

- Kitepower, with leading renewable developer RWE, tested the 100 kW 'Falcon' device in Co Mayo. Testing commenced in 2023 and concluded in July 2025.
- Skysails has tested its system at sites in Germany and Mauritius for several years. In 2025, it deployed their system in Taiwan.
- In September 2025, a 1 MW S1500 airborne wind turbine was launched in Xinjiang, China.

Cost

Germany has introduced a specific feed-in tariff for Airborne Wind Energy (AWE) under its Renewable Energy Act (EEG)., reported to be €120 - 130 MWh.

Timelines

With most technologies are at the testing and demonstration stages, commercial deployment is estimated to be one to five years away.

Potential to scale

Theoretically, the potential to scale is large in places where there is an abundance of space, such as offshore environments, or low populated areas such as deserts. Long term, the greatest scalability is offered by floating offshore deployment.

ESB Activity

ESB engages with leading OEMs on a regular basis.

Leading OEMs

SkySails Power, Kitepower, EnerKite, Kitemill.

Summary

The outlook for this technology is challenging due to technical, safety and cost issues that will need to be overcome. However, the technology does have attractive features such as an extremely light weight design (for kite type systems) and access to high winds. Germany and China are the leading players with this technology.

2. Storage

2. Storage (continued)

TRL
9

Sodium-ion Battery Storage

Sea salt harvesting

Sodium-ion batteries (Na-ion) are emerging as a sustainable and cost-effective alternative to lithium-ion (Li-ion) batteries. Sodium holds potential as an alternative to Li-ion, because of more abundant raw materials, lower fire safety risk, wider temperature operating conditions and higher depth of discharge capabilities. Na-ion use sodium ions as their charge carriers and are more favourable than Li-ion batteries in terms of their impact on mineral resource scarcity. Na-ion for stationary and mobile storage are at TRL 9 and have begun to scale up in recent years, led by projects in China.

Sample projects

- The largest hybrid Li-ion/Na-ion project in the world is the 200 MW/400 MWh project in Yunnan, China – 40 MWh of that capacity comes from Na-ion batteries supplied by HiNa.
- The largest pure Na-ion system is a 50 MW/100 MWh project in Hubei Province, China, with HiNa the battery supplier.
- The EU-funded SPRINT project, launched in January 2025, will optimise and demonstrate sustainable, and cost-effective quasi-solid-state sodium-ion batteries tailored for stationary applications.

Battery manufacturer CATL has launched a new Na-ion battery under the 'Naxtra' brand. It is the world's first mass produced Na-ion battery with an energy density of 175 watt-hours per kilogram, nearly equivalent to the Lithium Iron Phosphate (LFP) batteries popularly used in electric vehicles and grid energy storage systems.

Cost

European costs are difficult to obtain due to a lack of projects. Na-ion capex remains higher than Li-ion technology as of 2025, but the gap is closing. Advocates for Na-ion are claiming O&M costs are lower than for Li-ion, which would bring the overall costs closer to parity. However, the dramatic price falls in prices of Li-ion technology make the economics of competing technologies (including Na-ion) challenging. For example, BNEF reported global average Li-ion system prices (capital expenditure) had fallen 40% from 2023 numbers to US$165/kWh in 2024.

Timelines

Na-ion is significantly scaling up supply chains and production. An example of this is the CATL 'Naxtra' battery launch for cars and trucks. Na-Ion can be said to have achieved early commercial status in China.

Potential to scale

Sodium-ion has very significant scaling potential. Estimates vary widely, but the International Energy Agency (IEA) estimates sodium-ion batteries will account for around 10% of annual energy storage additions globally by 2030.

ESB Activity

ESB has shortlisted sodium ion battery technology as a key storage technology. It will continue to monitor the technology for grid scale applications.

Leading OEMs

CATL (China), Natron (US), Faradion (UK) BYD (China), HiNa (China).

Summary

Improvement in energy density and production scale-up could make Na-ion well positioned in the energy storage market. Batteries based on abundant raw materials such as sodium could reduce geopolitical risks and dependencies on specific regions. With ongoing innovations and substantial investments, their adoption in energy storage systems, renewable grids, and budget EVs is expected to soar in the coming years. However, it remains to be seen whether Na-ion batteries can develop a competitive advantage over Li-ion batteries.

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

Vanadium Flow Batteries in Oxford, UK (Credit. Invinity)

A flow battery is a rechargeable battery in which an electrolyte flows through the electrochemical cells from one or more storage tanks. There is a growing market in flow batteries for grid scale applications, particularly in the 4-24 hour duration range. Unlike Li-ion batteries, flow batteries have liquid electrolyte stored in external tanks rather than in each battery cell which decouples their power and energy. There are several different flow battery technologies being developed using different electrolyte chemistries at different TRL levels. Some examples include iron flow, iron-chromium, organic flow, zinc bromine & hydrogen/bromine batteries. Vanadium Flow Batteries (VFBs) are at TRL 9 and are already commercially available.

Sample projects

The China Huaneng Group has completed the main construction works on the world's largest vanadium flow battery project. The project features a 200 MW/1 GWh VFB system paired with a 1 GW solar farm. The Xinhua Ushi Energy Storage Project in China is operational and consists of a 700 MWh vanadium flow battery. Both projects are delivered by Rongke Power.

Cost

Costs greatly depend on the location and scale of the project. BNEF reported a global average fully installed cost of $444/kWh in 2023.

Timelines

VFBs are already available commercially and are expected to scale up in production in the next few years to meet the growing demand. Significant manufacturing capacity with higher levels of automation will be required.

Potential to scale

VFBs are now being deployed at much larger grid scale applications and their energy density is improving. China is constructing 30 GWh of VFB manufacturing capacity to meet global demand. With electrolyte production, vanadium mining, and battery manufacturing aligned, VFBs are expected to become a mainstream Long Duration Energy Storage (LDES) solution.

ESB Activity

ESB is engaged with 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 or elsewhere. As part of the study, ESB is conducting financial modelling to compare flow batteries with Li-ion at longer durations.

Leading OEMs

Invinity, Largo, Sumitomo, Cellcube, Rongke Power (RKP) and ESS.

Summary

Compared to Li-ion batteries, flow battery technologies offer advantages such as longer duration, more stable, longer cycle life and low degradation, but have higher upfront costs. In addition, the International Electrotechnical Commission is developing unified standards for vanadium electrolytes to ensure quality, safety, and scalability. Investment in local raw material supply chains, better manufacturing processes and larger scale projects will accelerate the deployment of flow battery technology.

2. Storage (continued)

TRL
8

CO_2 Battery Storage

CO_2 storage in Sardina (Credit. Energy Dome)

A CO_2 battery is an energy storage system that utilizes compressed CO_2 to store and release energy when needed enabling the long-duration storage of renewable electricity. The CO_2 battery is made primarily with standard industrial components such as compressors and turbines and using CO_2 as the storage medium allows for high-density energy storage without the need for extremely low temperatures. The CO_2 changes between its gaseous and liquid state in the charging and discharging process. This process operates in a closed loop cycle with no CO_2 being emitted into the atmosphere. This technology is suitable for durations of 8 to 24 hours. Due to the large footprint, it is less suitable in urban locations. The technology is currently at TRL 8.

Sample projects
Energy Dome has built a full-scale commercial 200MWh plant in Sardina, Italy close to its previous 4MWh demonstration plant, which is now decommissioned. The French multinational utility, Engie, has signed an offtake agreement for this plant which is currently connected to the grid.

Cost
Cost data is not available for CO_2 battery storage yet, but target costs for a full scale 200 MWh project are approximately €200-230/kWh. This may vary depending on market timing and build out costs in specific regions.

Timelines
Energy Dome are completing the commissioning stage of the plant in Italy after which some performance testing and component validation will be conducted by external parties later in 2025. Another 200 MWh project, in Wisconsin, US is planned to be completed in 2027.

Potential to scale
As projects are rolled out and performance data is validated the scale and number of projects are likely to increase significantly. Already, Energy Dome is developing projects using their full-scale solutions in US, India and Ireland. Google has announced its first long-term partnership for long-duration energy storage with Energy Dome to support multiple commercial projects globally.

ESB Activity
ESB and Energy Dome are conducting a study to access the feasibility of building a full-scale commercial CO_2 battery storage system in Ireland. ESB have visited the full-scale plant in Italy and have completed some financial modelling to access its feasibility in the market. Some further technical analysis will be conducted to access its performance and maintenance requirements at its location in Italy.

Leading OEMs
Energy Dome.

Summary
CO_2 batteries have several advantages including low environmental impact and reduced fire risk, proven components with reliable established suppliers, and a longer lifetime. An additional benefit is that the technology is synchronously connected to the grid – this negates some challenges with inverter connected storage systems. Due to the scale of the projects, obtaining planning permission will be an important consideration when choosing project locations. Energy Dome is expanding its supply chain which will mitigate projects risks as well as providing a cost competitive solution.

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

Advanced Compressed Air Energy Storage (A-CAES)

Hydrostor demonstration plant in Ontario, Canada (Credit. Hydrostor)

Advanced Compressed Air Energy Storage (A-CAES) is a next-generation energy storage technology designed to address the limitations of traditional Compressed Air Energy Storage (CAES) systems. Unlike legacy (diabatic) CAES, A-CAES eliminates the need for fossil fuels, making it a zero-emissions solution.

Diabatic CAES (TRL 9) uses fossil fuel combustion whereas A-CAES replaces this with a thermal energy storage (TES) unit, which stores thermal energy from the compression cycle.

A-CAES is currently at TRL 7 and proven at small scale in an operational environment. Full-scale plants are expected to come on stream in 2027-2030.

Sample projects

- A diabatic CAES project in Hubei, China, became operational in 2024, with 300 MW/1,500 MWh of capacity. The CAES project is designed to charge 498 GWh of energy a year a with round-trip efficiency of 64%.
- Two diabatic CAES plants have operated for over 30 years in Germany and in the USA.
- A 7 MWh Hydrostor demonstration A-CEAS plant is operational in Ontario, Canada.

Cost

BNEF (2024) reported a global average storage cost of $293/kWh for diabatic CAES storage for 2018–2024. Independent price data is not yet available for A-CAES.

Timelines

Hydrostor (A-CAES) is developing the Silver City project (200MW/1600 MWh) in New South Wales, Australia – it is scheduled to be operational by 2030. Hydrostor is also developing 500 MW projects in California and Ontario, with planned operations by 2030 and 2033.

Corre Energy (diabatic CAES) is developing a 320 MW project in Germany, using salt caverns with initial handover expected in 2027.

Potential to scale

A-CAES has a large potential to scale as sites could potentially be located in a wide range of geographies. This is an advantage when compared to pumped hydro storage for example.

ESB Activity

ESB and Hydrostor are at the early stages of exploring the potential for a large scale A-CAES plant in Ireland.

Leading OEMs in A-CAES

Hydrostor.

Summary

The diabatic CAES solution has not been adopted at a large scale due to the requirement for onsite combustion. A-CAES is promising large scale zero emissions storage solution. The key technology components are proven ‘off the shelf’ from leading OEMs. Advances in siting technology now allow ACAES to be deployed in hard rock formations, not just salt caverns. This significantly increases the worldwide availability of viable locations. However, high upfront capital expenditure are still a challenge.

2. Storage (continued)

TRL
9

Thermal Energy Storage

Thermal storage unit in Salerno, Italy (Credit. Migaldi)

Thermal Energy Storage (TES) is a storage technology that uses heat to store energy for prolonged periods. TES achieves this by heating a bulk storage medium such as molten salt, concrete or sand to temperatures as high as 1,200°C. This medium can be used later to generate electricity or for heating and cooling applications. This technology is most proven for applications with heat as an output, but manufacturers are also beginning to explore the electricity-heat-electricity (AC-AC) capabilities of TES for future integration into the electricity grid. TES technologies with heat as the output is at TRL 9. For grid scale AC-AC systems, EPRI report the leading technologies at TRL 6.

Sample projects

- The Finnish company, Polar Night commissioned a 1 MW/100 MWh 'sand battery' TES system in Finland in Q2 2025. This will provide heat to a local district heating scheme.
- Echogen, in partnership with Westinghouse, is developing a 50 MW, 24 hour, AC-AC TES system in Alaska. Completion is estimated to be circa 2030.

Cost

Spain has launched a €700 million program to increase its energy storage capacity, including TES. The funding will cover up to 85% of eligible project costs, with a maximum support of €300 per kWh for TES. TES has received a lot of financial investment in recent years. For example, Antora's Series B financing round raised $150m. BNEF (2024) reported a global average storage cost of $232 per kWh for thermal storage for the period 2018 – 2024. Note – this figure refers to heat as an output.

Timelines

As of 2025, several companies have successfully demonstrated the viability of TES in an electricity-heat capacity. However, the integrated AC-AC system is still in the development phase. The first large scale demonstrators (>10MW) are expected circa 2030.

Potential to scale

Some pre-existing concentrated solar power plants have demonstrated heat to electricity capacities of up to $110MW_e$.

ESB Activity

ESB has been engaging with the TES industry and is actively exploring potential solutions, both for power as an output and for heat as an output.

Leading OEMs

Leading OEMs focusing on heat as an output include, but are not limited to; Rondo, Polar Night, Brenmiller Energy, Kraftblok, Migaldi, Kyoto and Antora. Leading OEM's focusing on utility scale power output and integration with power plants include Malta Energy and Echogen.

Summary

TES systems for the provision of high temperature industrial heat are at TRL 9 and commercial projects are being rolled out. TES for grid scale, AC-AC systems, are at an early stage with the first large scale demonstrators (>10 MW) expected circa 2030. TES systems may also be integrated into existing thermal power plants. This is an interesting concept as it would provide a route to reduce the curtailment of renewables and the partial decarbonisation of thermal plants but is at an early stage.

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

Iron-Air Batteries

Form Energy factory in West Virginia, US (Credit. Form Energy)

Iron-air batteries are energy storage systems that use reversible rusting (oxidisation) of iron to store and release electricity. The leading company is US based Form Energy, who aim to achieve 100 hours of electrical storage using iron-air batteries. Eirgrid, in a document entitled 'A Call for Evidence on the Market Procurement Options for Long Duration Energy Storage' defined Form Energy's technology at TRL 7.

Sample projects

- Great River Energy is an electric cooperative based in Minnesota. Working with Form Energy, it is developing a proof of concept 1.5 MW /150 MWh project in Cambridge.
- FuturEnergy Ireland (ESB & Coillte joint venture) is developing a storage project, using Form Energy batteries, near Buncrana, Co. Donegal. The project received conditional planning permission in late 2024 but is the subject of a third-party appeal (as of August 2025).

Cost

There are no commercial demonstration projects available yet to validate the costs of iron air batteries. However, Form Energy is targeting costs of $20/kWh when the batteries reach commercial scale. This is an in-house cost projection and has not been validated independently.

Timelines

The Cambridge project referenced above is due to come on line in late 2025/ early 2026. Larger commercial scale projects ranging from 5 MW/500 MWh to 15 MW/1500 MWh, are projected for 2026-2028. Form Energy' commercial-scale factory in West Virginia has been operational since late 2024.

Potential to scale

If Form Energy achieves its technological and price point targets, the potential to scale is very large and is in the order of GWs.

ESB Activity

ESB has a Memorandum of Understanding (MOU) with Form Energy and engages on an ongoing basis.

Leading OEMs

Form Energy.

Summary

Iron-air battery storage is a rapidly developing and promising technology. It has the potential to achieve 100 hours of storage with low costs. One key strength of the technology is that the primary materials (particularly iron) are easily sourced and in plentiful supply.

2. Storage (continued)

TRL
9

Hydrogen Storage (Large Scale)

Underground Hydrogen storage in Austria (Credit. RAG Austria)

There are many ways of storing hydrogen both at the small and large scale. At the small scale, pressurised tanks (TRL 9) are a long-established method. At the large scale (TWh), research is ongoing into compressed hydrogen storage in underground caverns (aquifers, salt caverns, depleted gas fields, lined caverns, lined shafts). Salt caverns are currently considered the most mature for static underground storage (TRL 9).

Sample projects

Four hydrogen salt cavern sites are operational globally. However these are not yet coupled with a renewable hydrogen production facility. Instead, they are used as static storage for the chemical industry rather than cycling storage for the power industry.

- Spindletop, in Texas, is the world's largest hydrogen storage facility (>120 GWh).
- The world's first hydrogen storage facility in a depleted gas field was opened in 2023 in Austria. It has successfully injected and withdrawn hydrogen on a small scale. The next phase is a seasonal storage pilot as part of a €20m EU-funded programme.
- The €43m FrHyGe (France Hydrogen Germany) project seeks to demonstrate the use of natural gas commercial storage sites for hydrogen injection and withdrawal.

Cost

In an Irish context the cost of storing hydrogen underground is unknown, but it is expected that depleted gas fields will be the cheapest option available. The IEA Hydrogen TCP-TASK 42 Underground Hydrogen Storage report (2023) indicates that new salt caverns will cost $0.51/kWh of hydrogen stored. The figure for underground storage in porous media (i.e. depleted gas fields) is $0.2/kWh of hydrogen stored.

Timelines

The development of large-scale caverns for storing renewable hydrogen in Ireland is likely to be post-2035. Ireland has no proven existing salt cavern storage sites. Research suggests some potential in the Irish Sea, but costs would be much higher than onshore development.

Potential to scale

There is the potential for hydrogen storage to achieve TWh scale in Ireland.

ESB Activity

ESB formed a joint venture company, Kestrel DAC, with dCarbonX.

DCarbonX is subsidiary of Snam and Bord Gais Energy (a subsidiary of Centrica). Snam is a geological company which develops sub-surface assets for hydrogen and carbon storage. Centrica is developing Rough gas field for hydrogen storage in the North Sea off the UK's east coast.

Kestrel DAC is proposing to redevelop the decommissioned gas reservoir off Ballycotton in the Kinsale area gas fields for large-scale energy storage of renewable gas and renewable hydrogen. The consenting process for hydrogen storage at the retired Ballycotton natural gas field has commenced. The plan is to develop natural gas storage there in the early 2030s and transition to hydrogen storage when sufficient volumes become available.

Leading OEMs

SNAM (Europe's largest gas storage provider).

Summary

Hydrogen is considered as one of the leading options for seasonal storage of electrical energy at TWh scale. Its large scale capacity to store energy for long periods makes it an attractive solution for complementing the seasonal variability of renewable power. The most affordable options include underground storage in salt caverns and depleted gas fields. ESB is leading a project to redevelop one of the depleted gas fields in the Kinsale area as a reservoir for hydrogen to provide zero carbon energy storage for periods of low renewable power generation.

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

Bio-Derived Renewable Diesel

HVO at a Circle K refuelling station, Dublin Port

Renewable diesel can be used as a direct substitute for fossil diesel. It offers the potential to decarbonise a wide range of end uses including transport, heating and electricity generation. Most renewable diesel is produced by hydrotreating waste vegetable oils and animal fats through an established and mature process (TRL 9) called HEFA (Hydroprocessed Esters and Fatty Acids). This renewable diesel is generally known as HVO (Hydrotreated Vegetable Oils). There is, however, a limited availability of sustainably sourced waste animal fats and vegetable oils in the world.

The scaling up of renewable diesel production requires the development of alternative production pathways. Emerging technologies, which have much larger potential sources of feedstock, include the Gasification & Fischer-Tropsch processing of woody biomass and municipal solid waste (TRL 6). The Alcohol to Jet fuel process converts ethanol derived from grain and waste to jet fuel (TRL 7-8).

Sample projects

- Circle K and Certas have been expanding the availability of HVO across their network of forecourts in Ireland, offering a sustainable alternative to their customers for diesel vehicles.
- The FLITE project (Fuel via a Low Carbon Integrated Technology from Ethanol) which is supported by the Horizon 2020 program is building Europe's 'first of a kind' Alcohol to Jet facilities in the Netherlands. It aims to convert waste-derived ethanol to over 30,000 tons of sustainable aviation fuel per annum.

Cost

The cost of producing renewable diesel is very dependent on the production process and the feedstock used. Renewable HVO produced through the HEFA process costs between €1 – €1.50/litre whereas renewable diesel produced using the Gasification & Fischer Tropsch and the Alcohol to Jet processes are two to five times more expensive than HEFA-derived fuels.

Potential to scale

HEFA-derived renewable diesel has a relatively low potential to scale due to the limited availability of sustainable recycled vegetable oil. The implementation of proposed EU sustainability standards may also limit availability. The Gasification & Fischer-Tropsch and Alcohol to Jet pathways have a much higher potential to produce significant volumes (MT/annum) of renewable diesel given the volumes of available feedstocks these processes can utilise.

ESB Activity

ESB is actively tracking the market and is exploring ways it could sustainably incorporate HVO into its dispatchable thermal generation fleet.

Leading OEMs

HEFA-derived includes NESTE, ENI, Total. Alcohol to Jet includes Lanzajet, SkyNRG.

Summary

Renewable diesel (HVO) is a flexible, versatile drop-in replacement for fossil diesel and offers an attractive decarbonisation option for existing asset owners. The HEFA production process is developed and mature, but the potential supply of sustainable feedstock is limited. Renewable diesel production from the Gasification and Fischer Tropsch process has a much higher potential to scale but is more expensive. The Alcohol to Jet process has the potential to significantly scale up in response to the EU's ambitious sustainable aviation fuel targets.

2. Storage (continued)

TRL
9

E-Fuels

E-fuels, also known as electrofuels, are synthetic fuels that are chemically equivalent to their fossil counterparts. An e-fuel is produced synthetically from renewable power and renewable resources like water and renewable carbon dioxide (CO_2). The most established E-fuel production process begins by producing hydrogen, from water electrolysis, and combining this with biogenic or atmospherically captured CO_2 using a reaction called Reverse Water Gas Shift (RWGS).

This reaction transforms the hydrogen and CO_2 into a synthesis gas (syngas) that undergoes a secondary reaction process to form long-chain hydrocarbons like e-diesel, e-gasoline and e-kerosene. This secondary reaction process is known as Fischer-Tropsch synthesis. Another alternative that is gaining traction is the production of e-methanol.

The Fischer-Tropsch synthesis is at a very mature state (TRL 9). However, RWGS reaction is currently at a lower state of development (TRL 6). An alternative method to synthetically produce e-fuels is to initially produce methanol. Through a similar series of reaction pathways, methanol can then be processed into longer-chain molecules to form hydrocarbons. This method of synthesis is currently at TRL 7.

INERATEC 'Era One' project in Frankfurt, Germany (Credit. INERATEC)

Sample projects

- Although Sasol has been producing synthetic fuels since the 1950s from non-renewable sources, some companies have started to produce e-fuels using renewable feedstocks. One example is Infinium, a US-based company that has a Fischer-Tropsch-based plant in Texas. According to Bloomberg, it produces roughly 8,300 litres of fuel per day – these include e-diesel, e-jet and naphtha.
- In 2023, the HIF plant in Chile started a first-of-a-kind pilot using the methanol to e-gasoline process – it is now producing up to 130,000 litres of e-gasoline per annum. This fuel has been exported to Porsche in the UK in shipments of 24,600 litres.
- The German company INERATEC inaugurated its ERA ONE plant in Frankfurt in June 2025. With a nominal annual capacity of 2,500 tonnes of carbon-neutral e-fuels, it is the largest e-fuel plant in Europe.

Cost

The production of e-fuels is an energy-intensive process, and production costs are strongly influenced by the renewable electricity prices. The European Aviation Safety Agency reports that the cost of aviation fuel equivalent e-fuel in 2024 was €7,700-€8,500 per metric tonne. This is approximately 10 times more expensive than conventional fossil jet fuel.

Timeline

E-diesel is currently being produced in a couple of relatively small plants, but exponential growth is predicted in the next decade and this will be driven by UK and EU mandates for e-jet fuel in the aviation industry.

Potential to scale

There is a large potential to scale with a projected market size of $50 billion by 2030). The use of e-jet fuel is mandated (with stiff penalties for non-compliance) by the UK and EU from 2030 onwards, with an estimated EU-mandated demand of 600k tonnes of e-fuel per annum.

ESB Activity

Currently ESB is planning to develop a pilot project that is expected to produce around 400 litres/day of e-fuels.

Leading OEMs

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

Summary

E-fuels are a drop-in alternative for fossil-based fuels and can be produced with 100% renewable resources. The core technology is very mature, but there are challenges in the supply renewable feedstocks due to variability of renewable electricity and availability of renewable CO_2. Several companies are developing projects to fulfil mandated demands in the aviation sector. E-fuels are substantially more expensive than fossil-based diesel.


Fred. Olsen Windcarrier
BLUE TERN

3. Empowered Customer

3. Empowered Customer (continued)

TRL
9

Industrial Heat Pumps

Green houses in East Anglia heated by heat pumps

Industrial Heat Pumps (IHPs) are heat pumps used in an industrial setting that actively recover waste heat and which can provide temperatures up to 200°C. The TRL of IHPs varies according to the temperature output. According to the IEA's Technology Collaboration Program (TCP) on High Temperature Heat Pump (HTHP), IHPs achieving 120°C are at TRL 9, while IHPs achieving 160°C and above are expected to become commercial from 2026.

Sample project

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

The world's largest CO_2-based seawater heat pump started operation at Esbjerg, Denmark in November 2024. The 70 MW heat pump supplies heat to 25,000 customers through the local district heating network.

Cost

With higher capital and operational expenditure (CapEx), the economics of IHP can be challenging when compared to a gas equivalent. However, the costs are specific to each application and the availability of waste heat sources.

Timelines

The roll out of IHP is gaining momentum and the 2024 Climate Action Plan includes an action to deliver a roadmap to phase out fossil fuel for all heat usages under 140°C.

Potential to scale

IHPs have the potential to substitute all fossil fuel heating solutions under 200°C. The higher cost of electricity and the higher CapEx relative to gas installations are barriers to the rollout of IHPs. The technology will require grant support for adoption. In Ireland, the principal support system for IHPs is the Support Scheme for Renewable Heat, which offers CapEx grants of up to 40% or €1m depending on the temperature output and the system's coefficient of performance.

ESB Activity

ESB has signed a contract with one of Europe's leading food processors, ABP Food Group. Under the contract, ESB delivered an 870kW ammonia heat pump with 65°C water output and is currently working on installing a second project. ESB has deployed heat pumps at two large greenhouses in East Anglia in the UK. The total thermal output is 72 MW and the total area of the greenhouses is 29 hectares.

Leading OEMs

Everllence is offering hot water and steam generating heat pump solutions delivering temperatures up to 150°C and above when in cascade configuration.

Summary

The outlook for IHPs in Ireland is positive. The technology is developing and there is a good match with the low and medium temperature heat required in Ireland's food and beverage industry with the temperature output by IHP. Financial supports are currently required to overcome high upfront costs and the relatively low cost of gas solutions.

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

Vehicle to Everything Charging

V2G car sharing service, Utrecht, Netherlands (Credit. Renault)

Vehicle to Everything charging (V2X) is a term used to describe bi-directional power flow from an Electric Vehicle (EV) to other non-transport applications, such as to a home (V2H), to the grid (V2G) or to external loads (V2L). The technology is relatively mature (TRL 9), but the markets to monetise it are still emerging. Using V2X technologies, an EV can function as a battery storage system and participate in grid service activities such as demand time shifting, arbitrage or backup power if suitable infrastructure and permissions are in place.

Sample projects

There are an increasing number of large-scale pilots testing V2X technology and commercialisation across Europe and globally.

- The 2025 Utrecht Energized initiative in the Netherlands deployed 50 Renault 5 E-Tech EVs for car sharing and 50 bidirectional chargers. The objective is to charge the EVs using locally produced solar energy and discharging at peak periods. The initiative also promotes the uptake of car sharing over private vehicle ownership.
- Octopus Energy and BYD have launched the UK's first vehicle-to-grid (V2G) bundle. The all-in-one package includes a V2G-capable BYD Dolphin, bi-directional charger and smart tariff.

Cost

The charging hardware to provide V2X services are significantly more expensive than standard unidirectional chargers. In Ireland, there is no export tariff yet to sell stored energy in an EV through use of V2X chargers. Demand response and optimised charging/discharging schedules, based on market conditions, offer revenue potential for V2X. In the UK, Octopus offers free EV charging when users sign up to their V2G Powerloop trial.

Timelines

EVs, such as the Nissan Leaf, which use the Japanese charging standard (CHAdeMo), have availed of V2X services for many years. The EV industry in Europe is moving toward the CCS charging standard. Some recent EV models, using CCS2 or through direct AC connection, now have V2X capability. Outside Ireland, service providers such as The Mobility House and Octopus are already offering demand response V2G charging solutions.

Potential to scale

With the governments CAP24 target of 845,000 passenger EVs and 95,000 commercial EVs to be on Irish roads by 2030, the potential to scale is significant but questions around battery degradation and the limited number of compatible EVs need to be overcome to enable wide adoption of the solution.

ESB Activity

ESB Networks installed five domestic WallBox V2G chargers as part of the Dingle Project in 2021, and one V2G charger in Leopardstown as part of the RESERVE Project in 2019. Both projects trialled and tested the operability of V2G chargers and their effect on the local grid.

Leading OEMs

Most EV OEMs have V2X capabilities or plan to have them in the near term. There are several OEMs, such as WallBox and Nuvve, which already offer V2X chargers. The Mobility House and Octopus are leading the integration of chargers for demand response and wholesale energy markets.

Summary

As the global mass adoption of EVs continues, flexible EV charging and V2X will become an integral part of future demand side grid flexibility services. Deployment is currently uneven around the world, V2X commercial offers are available in countries like the US, UK and France, but not available yet in Ireland. Despite issues around public acceptability, technology availability and policy, the future for V2X in Ireland looks positive.

3. Empowered Customer (continued)

TRL
9

District Heating (Fourth and Fifth Generation)

DDDH pipes (Credit. RTE)

District Heating (DH) is a centralised heating system that uses one or more energy centres to generate and distribute heat to buildings, industrial or commercial premises via a network of insulated pipes. Fourth-generation district heating (4GDH, TRL 9) uses low-temperature water and integrates renewable energy sources, while fifth generation (5GDH, TRL 8) systems use ambient temperature networks with decentralized heart sources.

Heat sources include waste heat recovery, solar thermal, geothermal and heat pumps. These DH schemes will also include thermal storage to allow for peak shaving and demand response.

Sample project

The Tallaght DH Scheme is a 4GDH network capable of providing up to 3MW of heat to several public buildings and the TU Dublin – Tallaght campus. The energy centre uses low grade waste heat from a nearby Amazon data centre and upgrades the heat using two heat pumps. It is owned by South Dublin County Council and was co-developed by Codema. Fortum designed, built, and now operate and maintain the network. A planned expansion of the network is due to connect residential buildings.

Cost

DH costs vary substantially and become more commercially competitive in areas with a higher density of heat demand. A recent report by the Irish District Energy Association (IrDEA) published in May 2024 estimated that the Levelized Cost of Heat (LCOH) coming from a DH scheme supplied by heat recovered from a data centre and in a high heat density area is €93/MWh, which is competitive with an individual air source heat pump.

In Q2 2025, the Department of Climate, Energy and the Environment (DCEE) allocated €5 million from the Climate Action Fund (CAF) to support district heating projects' development costs.

Timelines

The 2024 Climate Action Plan sets out a target of up to 2.7 TWh of DH to be delivered by 2030, with up to 0.8 TWh by 2025. Dublin City Council is preparing a joint venture procurement for the delivery and operation of the Dublin District Heating System. The project is included in Dublin City's Capital Programme 2024-2025.

Potential to scale

District heating accounts for just 1% of Ireland's heating demand, but in other jurisdictions (notably the Nordic and Eastern European countries), DH has reached penetration levels of 50–90%.

The National Heat Study (NHS) 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 it comes to scaling of DH networks. A spatial analysis from SEAI, prioritizing the highest heat density areas, found that 50% of the 2.7 TWh target set out in the Climate Action Plan can be delivered in Dublin and Cork city.

ESB Activity

ESB is actively monitoring the development of DH in Ireland.

Leading OEMs

DH are large energy projects often run by utilities or energy services companies. Leading developers and operators in Europe, with operations in Ireland, are Veolia and Fortum.

Summary

Ireland is in the bottom five of EU countries for DH adoption. Successive Climate Action Plans recognise the role DH can play in decarbonising heat in Ireland and have set ambitious targets. Policy and financial supports will be critical to deliver on these targets.

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 9

Anaerobic Digestion & Biomethane

Anaerobic digester (Credit. College Proteins)

Anaerobic Digestion (AD) is a mature technology that processes organic waste and agricultural feedstock (e.g. silage) and converts it into usable products contributing to the circular economy. The two main products are digestate, which can be used as agricultural fertiliser, and biogas which is comprised of c. 60% methane & 40% biogenic CO_2. 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 around the world and is a mature technology (TRL 9) Compared to other EU countries Ireland has a strong potential opportunity to deploy further AD to support the National Climate Action Plan. The National Biomethane Strategy for Ireland (May 2024) sets out ambitious targets for growing the AD industry by 2030.

Sample project

Bia Energy owns and operates Ireland's largest AD plant located in Huntstown, Co Dublin. The feedstock includes waste products from the agricultural and food sectors. The facility currently uses the biogas to generate electricity, but it is being upgraded to produce biomethane. The biomethane will be injected directly into the gas network, which will be extended to the facility for this purpose.

Cost

The estimated cost to produce biomethane reported in the National Biomethane Strategy is between €120-150/MWh for a 50 GWh plant.

Timelines

AD deployment is expected to significantly ramp up in Ireland between 2025-2030. This will be enabled by the expected introduction of capital grants and the Renewable Heat Obligation in 2026-27. The national target is to deliver 5.7 TWh of indigenous biomethane in 2030 as outlined in the Climate Action Plan.

Potential to scale

AD has good potential to scale in Ireland. The target of 5.7 TWh of biomethane would cover 10% of Ireland's current overall gas demand. To take an example from a market leader, in Denmark where AD has been deployed at scale it is currently covering more than 40% of Denmark's Natural Gas demand.

ESB Activity

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

Leading OEMs

Leading developers include Bia Energy, Nephin Renewable Gas, CycleØ Group, CarbonAMS and Greengate Biogas.

Summary

AD has a positive outlook for growth in Ireland with a national target to create 5.7 TWh of indigenous biomethane per annum by 2030. To enable this, the National Biomethane Strategy for Ireland was published in May 2024. In Q2 2025, government approval for the Renewable Heat Obligation Bill was secured. The Bill provides detail on opening obligation rates of 1.5% in year one, and 3% in year two.

4. Carbon Capture Utilisation and Storage (CCUS)

4. Carbon Capture Utilisation and Storage (CCUS) (continued)

TRL
9

BioEnergy Carbon Capture and Storage (BECCS)

Wood chips and biomass for renewable energy

BECCS is the coupling of bioenergy with carbon capture and storage technologies to deliver carbon negative emissions. The natural capacity of growing biomass to capture carbon dioxide from the atmosphere – and then capturing and sequestrating the carbon dioxide resulting from the different bioenergy processes – generates carbon credits that can mitigate other hard-to-abate sectors.

There are several bioenergy processes that produce carbon dioxide as a by-product. The main three are: biomass combustion power plants or biomass combustion boilers; bioethanol production, and biomethane plants. The capturing technology varies depending on the bioenergy process, but the most mature options include amine absorption, pressure swing absorption and water scrubbing separation.

Sample projects

- The first biomass combustion BECCS plant started operation in 2020 at the 50 MW Mikawa Power Plant in Japan. It captures up to 50% of the CO2 produced by the plant, which burns palm kernel shells using an amine absorption process.
- In Sweden, BECCS Stockholm is building a project that will capture 800,000 tonnes of CO2 annually from an existing co-generation biomass plant. Construction has started and commissioning is expected in 2028.

Cost

The carbon reporting organisation CDR.fyi states that a tonne of carbon captured using BECCS has a 2030 breakeven average cost of $182, Frontier (a carbon removal fund) also reports similar values. The costs vary with the source of the carbon – the most expensive being power plants, followed by biomethane. Ethanol plants are the least expensive.

Timelines

Small and test facilities are operating globally. 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 BECCS in Ireland.

Potential to scale

The only operational biomass burning power in Ireland is operated by Bord na Móna in Edenderry, Co Offaly. It has the greatest potential to generate BECCS on the island. Ethanol plants such as distilleries also present an opportunity to create carbon negative emissions, but their potential is much less than the Edenderry plant. Finally, biomethane plants are a good source of biogenic carbon dioxide, but their dispersed nature make the transport and storage issue a big challenge.

ESB Activity

ESB does not operate any biomass power plant, but studies are being conducted while observing the BECCS industry activities.

Leading OEMs

Mitsubishi Heavy Industries, Capsol Technologies, Aker Carbon Capture, Shell, ExxonMobil, Chevron, Honeywell UOP.

Summary

BECCS represents an attractive alternative as a solution for providing carbon negative credits. With some flagship projects being constructed globally, the carbon markets are expected to offer BECCS carbon credits in the next couple of years. In Ireland, Bord na Móna has expressed its interest in capturing CO_2 from its biomass plant in Edenderry.

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

Biochar

Biochar. Source: Biogreen Energy, 2024

Biochar is a porous material comprising of >90% carbon. It has a high stability and permanence and is produced the pyrolysis process. This is a thermal decomposition process that occurs in an oxygen-deficient thermal environment. In the pyrogenic process, shredded feedstock materials are heated to temperatures of between 300-900°C and are converted into relative amounts of solid, liquid and gas components (char, bio-oil, and syngas), depending upon the pyrolysis technology employed.

End use applications of biochar include soil amendment (fertiliser supplement), animal feed, carbon sequestration or concrete aggregate. There are 100+ full-scale sites globally and the technology is defined at TRL 9.

Sample project

Novocarbo's Baltic Sea site in Germany was commissioned in 2023 and uses sawmill waste as the feedstock. The project has deployed two PX1500 machines from Pyreg and can produce 1,400+ tonnes of biochar per annum. It features feedstock drying, biochar packaging, and waste heat utilisation in the nearby district heating system.

Cost

The cost of carbon removal using biochar is €100–€200 per tonne of CO_2, which compares favourably with other carbon removal technologies. In the current carbon voluntary market, this technology has delivered the majority of the carbon credits purchased, and also the lowest costs.

Timelines

In Ireland, the biochar market is nascent and requires Irish based research to confirm findings from European projects – particularly around the permanence of the carbon sequestration. The EU Carbon Removal Certificate Framework (CRCF) has included Biochar in its scope, allowing standardised trading of Carbon Removal Certificates (CORC).

Potential to scale

Biochar has potential to scale in line with availability of feedstock and demand for the biochar.

ESB Activity

ESB keeps a watching brief on biochar technology developments and the biochar market.

Leading OEMs

Pyrolyser manufacturers include Pyreg, Biomechon, and Carboforce.

Summary

There is long-term potential to scale biochar in Ireland as the price of carbon increases. Its main benefit over other forms of carbon sequestration is that the storage medium is soil rather than requiring storage in a geological formation.

Globally, as new methodologies and standards for carbon removal are developed and refined, the role of biochar and similar technologies is likely to become increasingly integral to global carbon management strategies.

4. Carbon Capture Utilisation and Storage (CCUS) (continued)

TRL
9

Point Source Carbon Capture

Point Source Carbon Capture (PSC) involves the capture and processing of flue gas from a refinery, gas turbine, or other source to separate the CO_2 for storage. This process is close to net zero. Flue gas CO_2 content ranges from 5-90% depending on the process, and it requires different types of technologies for carbon capture from point sources.

These are mostly divided into pre-combustion, oxy-combustion and post-combustion. Here the focus is on post-combustion since it is the only alternative that does not require upstream modifications to the emitting process. Post-combustion carbon capture technologies include chemical absorption, mostly with amine-based solvents (TRL 9); solid adsorption (TRL 6); membrane separation (TRL 6) and calcium looping (TRL 7) according to the IEA. These TRL ratings are based on the technology selected for each case and depend on the point source CO_2 partial pressure, flow, contaminants, and other gas characteristics.

Northern Lights CCS project, Norway (credit. Equinor)

Sample project

In June 2025, the world's first carbon capture and storage (CCS) plant to sequester emissions from a cement facility was inaugurated in Brevik, Norway. The plant will capture 400,000 tonnes of CO_2 annually, representing 50% of the cement plant's total emissions. The captured CO_2 is liquefied and stored on-site until injection into the Northern Lights subsea CO_2 storage facility. Owned by Heidelberg Materials, the plant uses an amine-based solvent provided by SLB Capturi (formerly Aker Carbon Capture) to capture the carbon emissions.

Cost

According to the IEA and McKinsey, the estimated cost to capture flue gas CO_2 varies according to sources and partial pressures. Costs are as low as $25-35/ tonne for high partial pressure streams like bioethanol or ammonia production, Estimated costs range from $40-€120/ tonne for lower partial pressure flue gases like cement, power generation or iron and steel manufacturing. Transport and storage/ utilisation costs have to be added, while location and infrastructure availability are also key factors.

Timelines

The IEA reports that all the operational projects globally capture a total of 50.9 Mtonne of CO_2 per annum. Another 51.3 Mtonne of CO_2 per year are under construction and 327.4 Mtonne of CO_2 per annum is predicted by 2030. The current projects are mostly based on natural gas processing/LNG facilities (63.9%), while the planned projects by 2030 will cover a wider range of industries like hydrogen & ammonia (20.8%), power & heat (23.7%), and cement (8.6%). PSC is viewed as a key solution for hard-to-abate heavy industries.

Potential to scale

There is a large potential to scale for some of the CCUS technologies available such as chemical absorption, calcium looping, and solid adsorption). Public policy in some jurisdictions has enabled CCUS projects. These include CCUS clusters in the UK, and CCUS projects backed by the EU Innovation fund.

ESB Activity

ESB worked with an EU consortium of research bodies including a pilot project in Trondheim city, Norway; University College Cork; the University of Delft in Holland, Bord Gais, and Ervia to deliver the REALISE CCUS project.

Leading OEMs

Occidental Petroleum, Mitsubishi Heavy Industries, Equinor, Shell, Total, Saipem, ExxonMobil and BP.

Summary

PSC comprises technologies that aim to decrease the direct release of CO_2 into the atmosphere from hard-to-abate heavy duty industries. The technology based on solvent absorption has reached technical and commercial maturity and is at TRL 5-9 (depending on the flue gas origin). The cost of capturing CO_2 from point sources depends strongly on the CO_2 partial pressure in the flue gas, and is cheaper for those with higher shares of CO_2. As a technology that enables carbon-negative and carbon-neutral emissions, it is expected to be deployed widely in the next few decades. ESB has conducted R&D work in this field by supporting the REALISE CCUS project.

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

Direct Air Capture

DAC unit (Credits: SYNAERGY / Trinity College Dublin)

Direct Air Carbon capture (DAC) is a type of technology that captures CO_2 from the ambient air. Ambient air has between 0.03%-0.04% CO_2 so large amounts of energy are required to capture these diluted amounts. There are two DAC technologies available: liquid DAC (TRL 5-6) and solid DAC (TRL 7-8). Both technologies use cycles of absorption and release of CO_2. Liquid DAC requires higher temperatures to release the absorbed CO_2 than solid DAC or electricity to release the CO_2 using electrodialysis. The IEA estimates that the global DAC capacity is currently only 0.01 Mtonne of CO_2/annum, but it is growing quickly.

Sample project

In 2024, Climeworks inaugurated the Mammoth plant in Iceland. It is the largest DAC plant in the world, with a total capacity of 36 ktonne of CO_2/annum. This compares to 4 ktonne of CO_2/annum in the Climeworks plant installed in 2021. The Mammoth plant takes CO_2 from the air and dissolves it into water, which is then pumped underground where it reacts with subterranean basaltic rock to turn the CO_2 permanently into stone. The plant is planned to run with 100% renewable electricity generated from a local geothermal plant.

Cost

The World Economic Forum reports solid DAC prices of $600-1250 per tonne of CO_2 captured which is expected to decrease over time. In the voluntary carbon market, companies like Google and Microsoft have purchased DAC carbon credits at values as low as $100/tonne ($10m for 100,000 tonnes captured to be delivered in early 2030). Holocene, the credits' provider, is expecting to claim the US government's 45Q tax credit which is worth $180/tonne captured.

Timelines

The IEA expects to see an increase in DAC deployment within the next years if the right policy and incentives are developed. According to the US Department of Energy, by January 2025 there were 142 companies developing DAC technology.

Potential to scale

DAC has a large potential to scale. However, its energy requirements are an issue as these need to come from a renewable source to produce negative emissions.

ESB Activity

ESB is exploring a trial with Trinity College Dublin (SYNAERGY) to implement a 5 tonne/annum direct air carbon capture unit at an ESB site.

Leading Organisations

Climeworks, Global Thermostat, 1PointFive/ Carbon Engineering, CarbonCapture, Holocene, Heirloom.

Summary

DAC is a technology that could potentially provide negative emissions or a pathway to zero carbon for hard-to-abate sectors. However, several challenges regarding scale, costs and energy usage need to be addressed before DAC becomes a large-scale deployed technology.

4. Carbon Capture Utilisation and Storage (CCUS) (continued)

TRL
9

Nature Based Solutions for CCUS

Flooded peatlands – a nature based carbon capture solution

In Ireland, Nature Based Solutions (NBS) for CCUS include appropriately sited reforestation/afforestation, peatland restoration, and soil carbon sequestration. These allow ecosystems to better sequester carbon, contributing to climate mitigation and ecological integrity. NBS will be important in achieving Net Zero and are considered the most established of the CCUS technologies.

The UK Woodland Carbon Code indicates that the average rate of carbon sequestered is 647 tonnes of CO_2 per hectare over 100 years. In addition to carbon sequestration, NBS also bring multiple socio-environmental co-benefits, including biodiversity uplift, social amenity value, and water management. The carbon sequestration aspect often represents just a small amount of the overall benefit to society.

Sample projects

- As part of the Peatlands Climate Action Scheme (PCAS), Bord na Móna (BNM) is committed to peatland decommissioning, rehabilitation, and restoration measures. It is targeting circa 33,000 hectares in over 80 former Bord na Móna peat harvesting bogs.
- The ACRES (Agri-Climate Rural Environment Scheme) in Ireland offers farmers financial support to implement environmentally beneficial practices, including actions that enhance carbon sequestration.

Cost

The cost per tonne of CO_2 for nature-based carbon sequestration methods varies widely but is generally competitive relative to engineered solutions. For example, the United Nations REDD (Reducing Emissions from Deforestation and forest Degradation) framework reported the average cost of forest carbon ranges from \$30-50/tCO_2.

Timelines

Various nature restoration projects are ongoing in Ireland and will continue over several decades.

Potential to scale

The potential to scale is very large. For example, the Bord na Móna PCAS project is targeting 33,000 hectares of nature restoration. In addition, Nature Trust (Ireland) has an ambition of afforesting 1% (70,000ha) of Ireland's land mass with new native woodland. In the UK, a process is ongoing to integrate Greenhouse Gas Removals into the UK Emissions Trading Scheme, and this may include high quality UK woodland removals. This would have a positive effect on NBS scaling potential.

ESB Activity

ESB does not have any active projects related to NBS for CCUS but is keeping a watching brief on this topic.

Leading Organisations

BNM and Coillte, as Irelands largest landowners, are the leading NBS providers in Ireland. Numerous private non-profit companies are also operating in the sector.

Summary

Nature Based Solutions represent a proven methodology to sequester carbon as well as providing may other benefits, including biodiversity uplift, social amenity value, and water management. The scale for NBS projects is potentially very large. Care must be taken that activities are undertaken in harmony with all stakeholders, especially with the farming and rural communities.

5. Grid technologies

5. Grid Technologies (continued)

TRL 9

High Voltage Direct Current Transmission

North Sea Offshore HVDC Substation

High Voltage Direct Current (HVDC) is an electric power transmission system that uses Direct Current (DC) instead of the more commonly used Alternating Current (AC) for transmitting electricity. It is a relatively mature technology and is continuing to evolve (TRL 7-9). It has several advantages over AC systems including:

- Lower power loss over longer distances relative to equivalent AC lines
- It allows for independent control of power flows, making it useful for stabilising networks
- It enables the bulk transfer of low-cost forms of renewable electricity over long distances
- It enables subsea interconnection between countries
- It is the cost-effective transmission solution for integrating offshore wind in deep water (c. >60km offshore) with the onshore electricity grid.

Sample projects

- China's 1,100 kV UHVDC link, completed in 2019, is a 3,300 km HVDC link that has a 12 GW rating.
- The Rio Madeira link in Brazil connects the new hydro power plants in Porto Velho to Sao Paulo over 2,375 km and has a 6.2 GW rating.
- The 'Sun Cable' that is in development between Darwin (Australia) and Singapore is planned to include a 4,300km 2 GW subsea cable to supply up to 15% of Singapore's electricity needs.

Cost

The cost of HVDC connections depends on several factors such as power capacity, transmission medium and the converter technology. It offer cost advantages in specific scenarios such as long-distance transmission, subsea connections, and integrating offshore wind farms in deep water (> c. 60km offshore) with the onshore electricity grid.

Timelines

HVDC transmission lines are available to deploy, and the reducing costs of solar PV and storage are making these projects more economically viable. As offshore wind farms move further from the coast and into deeper waters (> c.60km), HVDC systems will become more prevalent as they are the cost-effective solution.

Potential to scale

HVDC transmission technology has the potential for significant growth, particularly as fixed and floating wind farms are developed further offshore and multi-terminal systems become prevalent across the energy system. Standardisation, scalability and strategic planning will be required for HDVC to enable its full potential, and these are the focus of current research and innovation for this technology.

ESB Activity

ESB is keeping a watching brief on HVDC developments. ESB sits on the Wind Energy Ireland 'Future Networks' working group, which covers HVDC technology.

Leading OEMs

Leading OEMs include SGCC, NR Electric, Zhongheng Electric. ABB, Siemens, GE, Hitachi and Mitsubishi Electric.

Summary

HVDC transmission technology will play a crucial role in efficient and reliable power transmission across long distances and in integrating offshore windfarms with the onshore electricity grid. The falling cost of PV and storage will enable further large projects that integrate areas with high natural resource potential with population centres. The significant planned growth in offshore wind will also drive the growth of HVDC transmission systems. In turn this will influence the design of wind turbine technology and transformer platforms.

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

Static Synchronous Compensator (STATCOM)

A Static Synchronous Compensator (STATCOM) system is integrated into the electricity grid to stabilise any fluctuations in the grid by absorbing or feeding in voltage supporting reactive power (depending on the requirements to maintain a stable system). STATCOM systems increase the reliability and capacity of the electricity network. This approach significantly improves grid stability and resilience as it reduces the risk of voltage drops and blackouts triggered by sudden events such as loss of wind generation or fault events occurring at peak times.

The Irish electricity system is being rapidly decarbonised. Large fossil fuel power generation plants (which would have traditionally provided reactive power) are being replaced by a wind and solar energy system, which is intermittent, variable and widely distributed. To compensate for the increasing levels of variable fluctuating electricity on the grid systems, grid operators are using STATCOM systems to help stabilise the grid.

STATCOMS can also provide additional functionality to dampen harmonic distortion that is increasingly being imposed on the power system from renewable generation sources such as solar and inverter fed wind generation. STATCOMs are at TRL 9.

STATCOMs at ESB site

STATCOMS are increasingly being employed with offshore wind to compensate for harmonics and reactive distortion that can be a consequence of the long undersea cables required to connect to offshore wind. The core technology behind STATCOM are power devices derived from electronic transistors which revolutionised computing in recent decades. IGBT (Insulated Gate Bipolar Transistors) are used to create large DC to AC converters that provide a fully controllable AC sinusoidal waveform that when injected into the grid can be used to compensate inductive and capacitive reactive power on the system and so control the voltage of the grid and maintain stability.

Sample projects

- ESB Networks recently installed three STATCOMS in Ireland on the 110 kV transmission system: Ballynahulla +/- 100 MVAr, Ballyvouskill +/- 100 MVAr and Thurles +/- 30 MVAr. All three incorporate active harmonic filtering. A fourth +/- 200 MVAr system connected at 220 kV is currently being planned.
- Northern Ireland Electricity Networks (NIE Networks) recently conducted a trial on a high voltage distribution circuit that experienced high voltage levels from distributed generation, and low voltage levels due to demand fluctuations.

Timelines

STATCOMs are a developing technology which will scale up to provide grid stability in line with the energy transition to zero carbon electricity systems.

Potential to scale

STATCOMS have significant potential to scale to complement the growth of variable, intermittent renewable sources.

ESB Activity

ESB recently commissioned three STATCOM systems in Ireland and it was the lead consultant for a system with EWA (Electricity and Water Authority) in Bahrain. The NIE Networks team are also trialling the use of STATCOM on the distribution network in Northern Ireland.

Leading OEMs

Siemens, Hitachi, RXHK, American Superconductor Corp. and GE Vernova.

Summary

STATCOM systems provide a technical solution for maintaining a stable and reliable electrical grid. These solutions will become increasingly important as the energy system transitions to power from intermittent renewable energy technologies. STATCOM provides a solution which allows network operators to improve voltage stability, enhance grid reliability, support renewable integration, and control reactive power flows in their networks.

5. Grid Technologies (continued)

TRL
5

High Temperature Superconductor Cables

A high temperature superconducting cable (or tape) is made from a superconducting material that exhibits superconductivity when cooled by liquid nitrogen to approx. −180°C. The term 'high temperature' is relative to other superconducting materials that operate at much lower temperatures. Superconducting transmission cables are nearly perfect electrical conductors and use the phenomenon of superconductivity to transmit large amounts of electricity over long distances with very low losses.

They have only been used in relatively short connections to date and a medium distance connection demonstration has yet to be developed, so the technology is at TRL 5. High temperature superconducting cables offer several advantages over conventional power cables including:

- Near perfect conditions for transmitting large amounts of electricity over long distances.
- Maximum power transmission in a limited space – one superconducting cable can transmit as much power as five conventional cables
- Increased public acceptance due to their low visual impact and low costs to build compared to new transmission lines.
- Shorter installation times compared to conventional cables.

Superconductor demonstration project, Blyth, UK (Credit. SuperNode)

Sample projects

- The Shingal project in South Korea connects the 154 kV substations of Shingal and Heugdeok, which are one kilometre apart. The system was built in 2019 and is operating as planned since commissioning. KEPCO (Korea Electric Power Corporation) is investigating further projects.
- SuperNode recently demonstrated the transmission of 5,000 amps through 30 metres of a new cable design, which uses a polymeric cryostat, at the Blyth technology centre in the UK.
- The EU's SCARLET project comprises 15 industry partners and is funded through the Horizon Europe scheme. The project aims to set common industry standards for high power superconducting cables and to demonstrate a full scale bipolar 1GW transfer.

Cost

The costs for high temperature superconductor cables are estimated by OEMs to be lower than for conventional systems. However, no large-scale demonstration system is available yet to validate the cost estimates.

Timelines

High temperature superconducting cables are expected to reach TRL 8 over the next ten years. A key focus area for their development will be the establishment of long-term ageing test facilities.

Potential to scale

High temperature super conducting cables have the potential for significant growth, and to be an important enabler of high levels of interconnection and renewable electricity. Standardisation and scalability of the cryogenic systems will be required to enable the technology's full potential.

ESB Activity

ESB does not currently have any active projects related to superconducting transmission lines but is keeping a watching brief on this topic. This includes ongoing and regular discussions with OEMs, other utilities and Council on Large Electric Systems (CIGRE) experts. ESB's HV and MV network has been fully ducted since the early 2000s; this means that existing design cables can be pulled out of the ducts and new superconducting cables installed without having to re-excavate the network. Retrofitting superconducting cables in the future can be undertaken without massive disruption and costs.

Leading OEMs

VEIRs, NKT, SuperNode, Fujikura Ltd, BASF, Nexans, Thevas GmbH.

Summary

High temperature superconducting transmission cables offer minimal losses, smaller diameter, and the potential to transmit much larger amounts of electricity compared to conventional cables. As the technology develops and matures, these cables may play an important role in accelerating the integration of large amounts of renewable energy into the electricity grid, and also in sustaining grid reliance.

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

SF_6-Free Equipment

SF_6 is a chemical compound that is widely used as an insulating gas in electrical equipment. Technologies containing SF_6 are widely used in electricity networks, mostly at medium voltage (MV) and low voltage (LV) levels. These technologies are used in switchgear to isolate and protect different sections of the grid such as switchboards, circuit breaker, metal enclosed switchgear and gas isolated switchgear. According to Schneider Electric, over 30 million units worldwide of MV switchgear uses SF_6 – 10 million of these units are in EU member states. SF_6 has a high global warming potential and a long atmospheric lifespan so the industry is committed to transitioning to an SF_6-free grid. There are a number of potential solutions which are being researched and developed. Leading solutions are at TRL 9 and include:

- Air insulated switchgear – this uses air as the insulation medium instead of SF6
- Gas insulated switchgear – this uses alternative gases such as mixture of air, synthetic gases and nitrogen as the insulation gas
- Solid insulated systems – these use solid insulation materials with electric insulation properties
- Vacuum insulated switchgear – this uses a vacuum environment as the insulation medium.

Metal enclosed switchgear

Sample projects

E-REDES (transmission and distribution system operator in Portugal) has run a programme with manufacturers and technology providers since 2021. This includes testing SF_6-free MV switchgear with vacuum switching and using solid insulation media (up to 24kV).

EON grid operators are currently running pilot projects at MV and HV levels using dry air and vacuum for insulation and braking. At MV level they have installed dry air insulating switch panels at 24kV and at HV levels (110kV). It is trialling dry insulation with a vacuum circuit breaker complemented by dry air instrument transformer sets.

i-DE and Enedis are also evaluating SF_6-free equipment such as dry air with vacuum breaking at MV level, and alternative fluorine gas at HV level in collaboration with number of different manufacturers.

Costs

There are insufficient commercial demonstration projects to validate the costs.

Timelines

Development and testing is underway and there is close collaboration between the industry and technology providers.

Potential to scale

There is large potential to scale once the switchgear and circuit breakers can meet reliability criteria through their lifecycle.

Leading OEMs

Hitachi Energy, ABB, Schneider Electric, CO7 technologies.

Summary

Distribution system operators are transitioning to an SF_6-free grid. This will require close collaboration between equipment manufacturers to ensure strong reliability criteria throughout the lifecycle. New systems need to prove they are as reliable, cost effective and safe as the existing systems. The technology also requires further RD&D.

Glossary

AD	Anaerobic Digestion
AWED	Airborne Wind Energy Device
BESS	Battery Energy Storage System
BNEF	Bloomberg New Energy Finance
CAP	Climate Action Plan
CAPEX	Capital Expenditure
CCUS	Carbon Capture Utilisation and Storage
DAC	Direct Air Capture
DH	District Heating
EPRI	Electric Power Research Institute
EV	Electric Vehicle
FLOW	Floating Offshore Wind
HVDC	High Voltage Direct Current
HVO	Hydrotreated Vegetable Oils
IHP	Industrial Heat Pumps
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
NREL	National Renewable Energy Laboratory
Na-Ion	Sodium-ion batteries
OEM	Original Equipment Manufacturer
PSC	Point Source Capture
SMR	Small Modular Reactors
TES	Thermal Energy Storage
TRL	Technology Readiness Level
VFB	Vanadium Flow Batteries
V2X	Vehicle to Everything
WEC	Wave Energy Converters

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