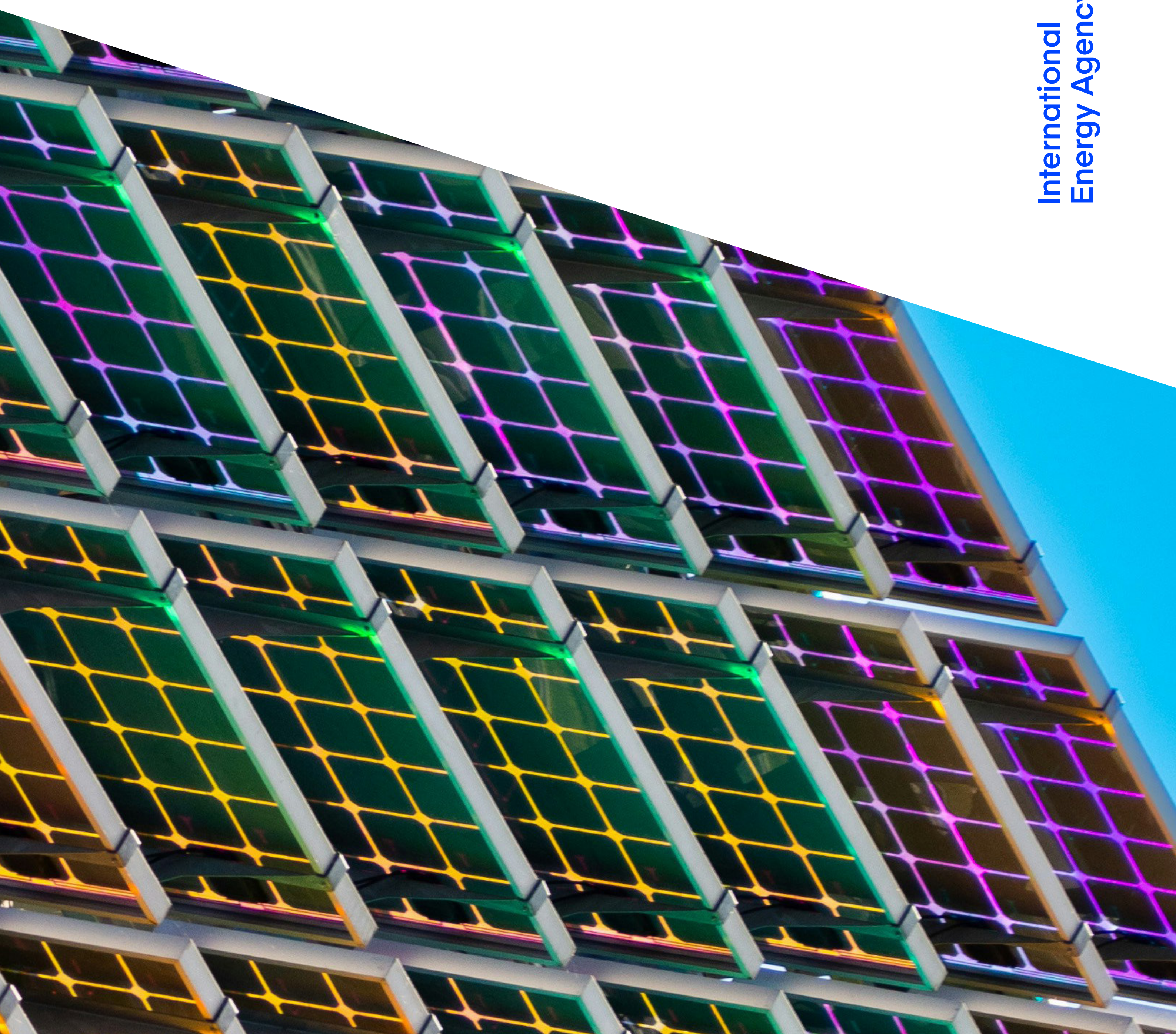
The State of Energy Innovation

International Energy Agency



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Abstract

Global energy innovation is evolving rapidly, shaped by technological advances, increased public and private investment, and a shifting international landscape. This report provides a comprehensive assessment of recent progress and emerging challenges in energy technology innovation, drawing on over 150 innovation highlights and a survey of practitioners across 34 countries. It analyses trends in public and corporate R&D spending, venture capital flows, and technology demonstration efforts, highlighting an increasingly international landscape, with emerging economies making strides alongside traditional leaders.

The report documents the increasing focus on low-emissions, modular and mass-manufactured technologies, as well as launching a set of 18 “races” to encourage faster progress towards key demonstration milestones. It identifies areas where new approaches to policy support are being developed to use public funds more effectively, but also highlights areas where more efforts are needed to address barriers to scale-up and attract private capital.

The report includes focus chapters on three dynamic fields, namely diversification of battery mineral supplies, application of artificial intelligence to energy innovation, and development of carbon dioxide removal technologies. The analysis provides a data-driven foundation to inform policy makers, industry and other stakeholders on the state of energy innovation worldwide and the importance of sustaining innovation momentum over the long term.

Acknowledgements, contributors and credits

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Executive summary

Today's energy technology landscape is highly dynamic. Innovations span a wide range of countries and technology areas, both emerging and established. These advances have implications for energy system planning and, ultimately, for the world economy. Whether incremental or disruptive, they are the products of government support, market expectations, finance, knowledge-sharing and accessible R&D and test facilities. It is testament to the efforts of energy innovators around the world that decision makers today can choose from a range of technology options to address strategic goals for all parts of the energy system. However, technological progress to tackle existing challenges and unlock new industrial opportunities relies on well-functioning innovation ecosystems and cannot be taken for granted.

This report provides a unique global review of progress and challenges in energy technology innovation. It follows the IEA's first Energy Innovation Forum, which took place in 2024 alongside the IEA Ministerial. It is designed to inform the global energy innovation agenda at a time when energy innovation is increasingly at the core of countries' competitiveness, security and resilience strategies, as well as those for addressing climate change. It is also a moment when uncertainties and emerging weaknesses could slow progress if not addressed. In addition to analysis of available data, the report draws on a dataset of over 150 energy innovation highlights from the past year, covering 45 countries and compiled with expert help from the IEA Technology Collaboration Programmes and a survey of almost 300 practitioners from around the world.

All phases of innovation, up to the early adoption of a new product in the marketplace, are covered in the report. After a new idea makes its way from the drawing board to a prototype and then out into the world, the pathway to maturity can be long, and success is not guaranteed. Even after products are first adopted, there is still a cost and performance gap with established technologies that policy attention must address. Across the innovation phases there are no simple metrics for measuring progress. However, many important insights into the health of the energy innovation system can be gleaned from data on R&D spending (a gauge of the effort directed to key challenges), patenting (a first-order indicator of R&D outputs), venture capital (VC) fundraising (a sign of the expected market value of new technologies), new product launches and competitiveness.

Spending on energy innovation has widespread pay-offs

Public and corporate energy R&D spending have risen in recent years, at around 6% per year in real terms. The latest available data indicate that direct government spending on energy R&D globally grew again in 2024, above the USD 50 billion of the previous year, but the rate of increase may have slowed. Initial indications of spending in 2024 in the United States and Canada suggest flatter year-on-year growth, balanced by larger increases in Japan and Norway.

Not every funded project will give rise to a radical new technology, but the impacts of this spending promise to be far-reaching. Estimates for the United States suggest that government R&D spending can generate economic returns to society over the following years that are thirty times higher than the costs. Average public energy R&D spending rose to an all-time high of 0.1% of GDP in the 1980s in IEA Member countries, in response to the energy security crises. Three-fifths of this went to nuclear, and from 1980 to 2000 nuclear power grew nearly fourfold in these countries, moderating demand increases for imported oil and gas. Today, these countries spend just over 0.04% of GDP on energy R&D, with nearly 60% in three areas – energy efficiency, nuclear and renewables.

The impacts of energy technology innovation are also visible at the level of trade balances. The implementation of horizontal drilling and hydraulic fracturing enabled the United States to shift from importing 46% of its oil and natural gas needs in 2000 to exporting the equivalent of 10% of its demand today. Innovation in batteries, electric vehicles (EVs) and their manufacturing enabled China's oil imports to be 8% lower in 2024 than if these EVs had been conventional cars. At around USD 200 billion per year, nearly 30% of the global value of technologies that became widely adopted only relatively recently – namely solar PV, wind, EVs and their batteries, electrolysers and heat pumps – is traded internationally.

Energy R&D can also bring societal benefits, for example by generating spillover benefits for other sectors. Initial research into rechargeable batteries to address renewable electricity variability led to the invention of lithium-ion batteries, which enabled smartphones. Once proven in portable devices, the technology was then adopted by the energy sector for EVs and electricity grids. Other technologies, such as those for appliance energy efficiency and payments for off-grid solar PV, have alleviated energy poverty and raised energy access.

The global landscape of energy innovation is changing

The United States, Japan and Europe led energy technology innovation for the past century, but today's innovation landscape has shifted. China became the largest single country for energy patenting in 2021, overtaking Japan and the United States. More than 95% of China's energy patenting in 2022, the latest year for which data are available, was in low-emissions technology areas. Globally, between 2000 and 2022, low-emissions energy patenting was four-and-a-half times that for fossil energy.

Today, more innovation effort goes towards small-scale and modular energy technologies such as batteries and electrolysers, but there are international differences. Around half of China's energy patenting and 90% of its venture capital (VC) is directed to mass-manufactured and modular low-emissions technologies, and innovation in these areas has helped underpin China's lead in several energy technology supply chains. In Europe too, around 50% of energy patenting is for smaller-scale low-emissions technologies, but it is also active in large engineering projects that generally have more uncertain impacts on long-term competitiveness. Energy inventions from the United States are more equally spread across fossil fuel as well as large- and smaller-scale low-emissions technologies, and its large VC market has the capacity to place bets on all of them.

Ambitious policies have attracted private capital to energy innovation, but headwinds are mounting

Trends in VC show the importance of policy and markets for attracting capital to energy innovation. Fundraising by energy start-ups halved after the "cleantech bust" of 2011 to 2015, but turned around sharply between 2015 and 2022, rising 570%. Key to this switch were the higher expectations after the 2015 Paris Agreement for policy to underpin markets for low-emissions technologies, as well as low interest rates and cost declines for cornerstone products like solar PV and batteries. Even if only a small fraction of the 1 800 energy start-ups that raised VC funding in 2021-2022 meet their scale-up goals, the impact on energy by the 2030s promises to be very significant.

In total, since 2015, USD 230 billion has been injected into energy start-ups, and expectations for this market continue to grow. Investors and governments are increasingly harnessing the VC model for honing energy technologies via rapid prototyping, manufacturing and exposure to competition in the market. Our latest projections put the total value of this market for key low-emissions technologies at over USD 2 trillion 10 years from now under current policy settings. From 2010 to 2014, start-ups in China and Europe raised just 3% and 15% of global energy VC, respectively. In 2020 to 2024 their combined share rose to almost 50%, while the United States remained the single largest VC market.

Today's more difficult conditions for VC funding raise cashflow concerns. In 2023 and 2024, annual energy-related VC funding declined by more than 20%. While VC funding has in general dropped due to inflation, the situation is compounded by uncertainties about political commitments to the climate policies that many start-ups depend on to drive demand. It is of special concern for firms with demonstration-scale or larger projects, which are costlier than prior stages.

An exception to the overall VC downturn is artificial intelligence (AI), which doubled its fundraising in 2024. While this signals an opportunity to attract capital to the interface between energy and AI, it also raises the possibility that a wave of AI enthusiasm could draw funds away from energy innovators. Nevertheless, early-stage investment in energy storage and batteries also remains robust, and there were increases in funding in 2024 for start-ups working on technologies for nuclear, synthetic fuels and carbon capture, utilisation and storage (CCUS) among other areas.

Corporate energy R&D spending has been growing three times faster than GDP, led by automotive companies, who now fill 13 spots in the list of the top 20 firms by energy R&D budgets. This growth highlights how innovation spending is triggered by regulation and competition. Spending has also been boosted by Chinese firms that have allocated increasing sums to R&D as their balance sheets have grown. Three Chinese state-owned energy companies now rank among the top ten largest corporate energy R&D spenders globally.

Races to demonstrate and scale up innovative energy technologies are taking shape

Addressing climate change will require significant advances in innovation. For example, around 35% of the emissions reductions needed to enable net-zero CO_2 emissions globally still rely on technologies not yet demonstrated at commercial scale. Large-scale first-of-a-kind projects face a range of non-technical challenges related to finance, business models, public support, safety standards, infrastructure, tariff design and offtake contracts. Overcoming these hurdles will be key to unlocking major benefits – the market size for innovative, near-zero emissions materials, such as steel and cement, is set to exceed USD 25 billion by 2035 under current policy settings.

The IEA tracks 580 demonstration projects that are aiming to gather essential operational experience by 2030. Around USD 60 billion in public and private financing has already been allocated to these projects in areas such as hydrogen-based fuels production, advanced nuclear designs, floating offshore wind and CCUS. However, most have not yet reached a final investment decision, and inflation and policy uncertainty have caused delays. Funding is highly concentrated, with only 5% for projects outside North America, Europe and China, and skewed towards energy supply, with heavy industry and transport sector projects representing just 17% of the total funding for projects under construction.

Corporate R&D in heavy industry and long-distance transport has not been rising as a share of revenues. The aviation and shipping sectors spent less on R&D in 2023 than in 2015. Cement and iron and steel companies increased their R&D spending as a share of revenue over the period, but far less than renewable energy equipment companies, which raised their R&D spending per unit of revenue by around 70% – to a level that is nearly three times higher than that of the cement sector. Yet heavy industry sectors require research and demonstration spending, calling for government support and international co-operation on major demonstration projects to share the costs within sectors.

We have identified 18 "Races to Firsts" demonstration challenges for important emerging energy technologies to track and encourage progress. These are key milestones that we believe to be mostly achievable within around 5 years with sustained policy support. They include a range of innovation across the entire sector, from the first building cooled with solid-state air conditioning, to the first repeatedly deployed small modular nuclear reactor, the first carbon-free flight and the first low-energy intensity ammonia production. They are all pertinent to a variety of different policy goals associated with the energy sector, and the IEA will track progress by the frontrunners as a means of recognising excellence and identifying areas for action.

The health of all parts of the innovation system determines the state of energy technology innovation

The recent innovation highlights presented in this report cut across all phases of the innovation process, from R&D to pilot, demonstration, fundraising and the launch of new products. In 2024, significant energy R&D advances included record-breaking efficiency for solid-state cooling that could avoid environmentally harmful refrigerants, if scale-up can be achieved. High-confinement plasma for nuclear fusion was maintained at steady-state for around 20 minutes for the first time by two different research groups. A prototype solid-state EV battery that could allow cars to be charged in nine minutes was reported, and trials were undertaken for higher-speed geothermal drilling through hard rock. Among larger-scale projects, first-of-a-kind progress was reported for perovskite PV manufacturing, ammonia use as a marine fuel, underground thermal and compressed CO_2 long-duration energy storage, lithium recovery from geothermal brine, cellulosic bioethanol facilities and CCUS for cement production, among others. These projects are supported by countries including Australia, Brazil, China, Finland, Germany, Italy, Japan, Singapore and the United Kingdom.

A healthy innovation ecosystem generates progress in each phase for each technology area each year, and brings them to the market over time**.** The highlights, compiled by the IEA from stakeholder inputs, show that some technology areas – including battery technologies, CCUS, critical mineral sourcing, geothermal and solar PV – made significant recent advances across all main innovation phases.

Battery minerals, innovating with AI and carbon dioxide removal are in the spotlight for international co-operation

The diversity and resilience of battery mineral supplies can be improved with innovation in mining, recycling and battery chemistries. Cathodes with higher iron content and less nickel and cobalt, both of which have faced supply chain volatility, have rapidly taken a nearly 50% share of the global EV market. Continued support for solid-state and lithium-sulphur battery research is needed, alongside creation of markets for new sources of lithium and clarity on recycling standards.

Applying AI to accelerate energy innovation can reduce search times for new energy materials, including for cathodes, electrodes, CO_2 capture, bioenergy and synthetic fuels. However, most successes are currently concentrated at the earliest innovation stages. To fulfil AI's potential to reduce costs and democratise energy innovation, open access databases, reduced barriers to "self-driving labs", and attention to scale-up are needed.[1]

Innovation in carbon dioxide (CO_2) removal is being spurred on by private capital mobilised by carbon credits. By 2024, a total of 140 start-ups had been launched to pursue 13 different ways of removing CO_2 from the atmosphere and preventing its re-emission. However, most of the USD 4.8 billion spent to date has been on just two approaches – direct air capture and bioenergy with CO_2 capture and storage. To bring others to the market, more effort is needed on monitoring long-term performance and procurement of high-quality credits.

Ten areas for policy attention for the next year

Energy innovation policy is a dynamic area of government activity worldwide. Policy support is especially important in a sector marked by high barriers to entry such as capital intensity, long lead times, safety standards and the need for extensive physical infrastructure. These factors disadvantage new entrants – and necessitate policies that encourage experimentation via multi-year hardware-led projects. Encouragingly, we see creativity in policy design, including for debt products to address scale-up risks, prizes that quicken the learnings from grant-funded R&D, and open access testing. We also see opportunities to reinforce international co-operation as geopolitical factors and shifts in

[1] A special IEA report on energy and AI will be published on 10 April 2025. It will cover the implications for energy innovation and many other applications of AI to optimise energy supply and use, as well as exploring datacentre electricity supplies.

government priorities could otherwise squeeze near-term access to capital and limit how new ideas are exchanged internationally.

Consultations undertaken for this report revealed areas where more policy attention is sought, and these are combined in 10 priorities.

- **Raise public energy R&D and demonstration spending** to attract private sector co-funding, boosting competitiveness and growth.
- **Ensure that the overall level of public and private support remains stable** in priority areas through economic cycles**,** maintaining access to operating capital.
- **Co-operate to bring a global portfolio of large-scale energy demonstration projects to fruition**, especially for near-zero emissions steel and cement, aviation (including fuel production) and CO_2 removal.
- **Ensure that publicly funded research supports accessible training datasets** so that energy innovators can grasp the full potential of AI-driven R&D.
- **Support access to testing facilities and "living labs"**, which can significantly shorten times to market for building energy management, geothermal, long-duration energy storage, heat networks and others.
- **Work to reduce bureaucracy and align processes with innovators needs**. Experiences with creative solutions – including permanently open calls, shared evaluations and multi-stage prizes – should be shared among governments.
- **Tailor support to each technology's innovation needs**. In sectors such as building energy efficiency, the critical bottlenecks are largely non-technical.
- **Strengthen energy innovation systems in emerging and developing economies**. There is untapped potential for more effort within these countries, among countries facing similar challenges, and via international partnerships.
- **Maximise innovation impacts from public investments** in first-of-a-kind projects by sharing findings and policy experiences during project implementation.
- **Foster markets that give confidence in robust future demand** for the products of the most successful innovators**.** Government support can spur demand, competition and competitiveness.

Over **150** energy innovation highlights from the past year across **45** countries

Leading to 65 updates of technology readiness levels in the IEA Energy Technology Guide, which tracks 600 energy technologies under development globally.

Energy innovation is increasingly at the core of countries' **competitiveness and resilience** strategies

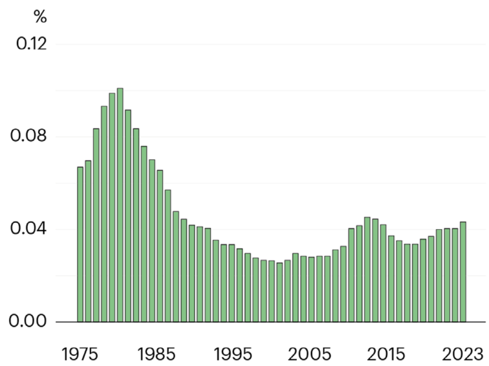
Emerging uncertainties and weaknesses could slow progress if not addressed.

1 800 energy start-ups raised VC funding in 2021-2022, and **1 400** more since then

promising a tidal wave of impact even if only a fraction succeeds.

Public and corporate energy R&D spending have been rising, at around **6%** per year in real terms

Public energy R&D spending reached USD 50 billion in 2023. It looks likely that it rose in 2024, but growth may be slowing. Governments spend 0.04% of GDP on public energy R&D today. This is less than half the level spent in 1980 in response to the energy security crises.



Energy R&D brings **benefits to society and the wider economy,** not just for the energy system

Mass-market spillovers from energy R&D

- Initial Li-ion battery R&D was for storing renewable power → Li-ion batteries for smartphones and electronics
- Processing seismic data to find oil and gas → Processing musical data for auto-tune

Unconventional oil and gas technologies

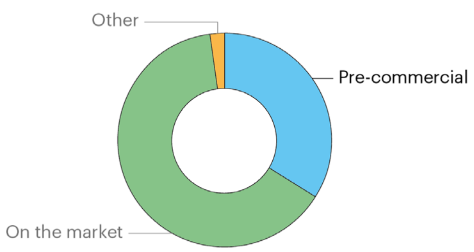
- 2020: United States imports 46% of its oil & gas needs → 2024: United States exports the equivalent of 10% of its needs

Battery EV and manufacturing technologies

- 2024: Share of EVs in car sales in China reaches 50% → 2024: China imports 8% less oil

35%

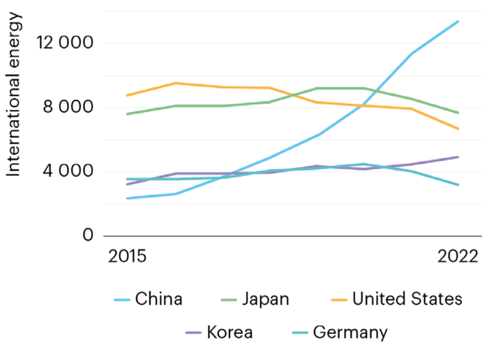
of the emissions reductions needed to enable carbon neutrality by mid-century globally, still rely on technologies not yet demonstrated at commercial scale.



Since 2015, **USD 230 billion** has been injected into energy start-ups

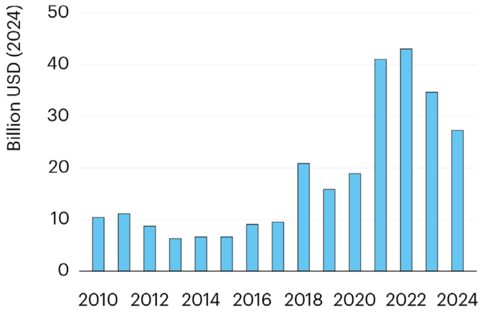
China became the largest single country for energy patenting in **2021**

Over 95% of China's energy patenting in 2022 is in low-emissions technology areas. Between 2000 and 2022, low-emissions energy patenting outpaced fossil energy patenting by 4.5x.

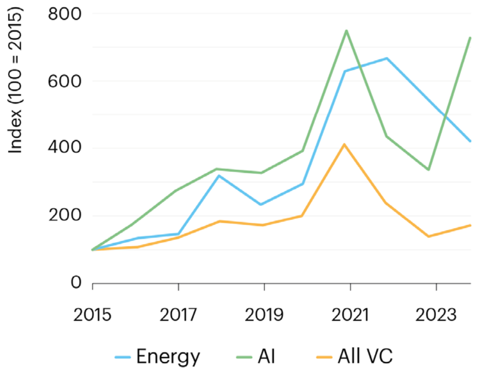


Policy and technological change attract capital to **energy innovation**

Energy-related VC fundraising boomed from 2015 to 2022, reaching the level of all public energy R&D to boost scale-up of researchers' inventions. But capital availability is now 37% below the high of 2022.

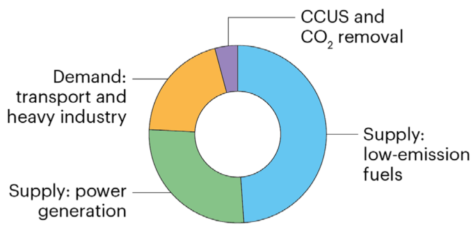


Thriving **AI sector** attracted more of the available VC capital in 2024



The value of key low-emissions technology sales is set to exceed **USD 2 trillion** by 10 years from now

Many large-scale demo projects **still need** to take FID

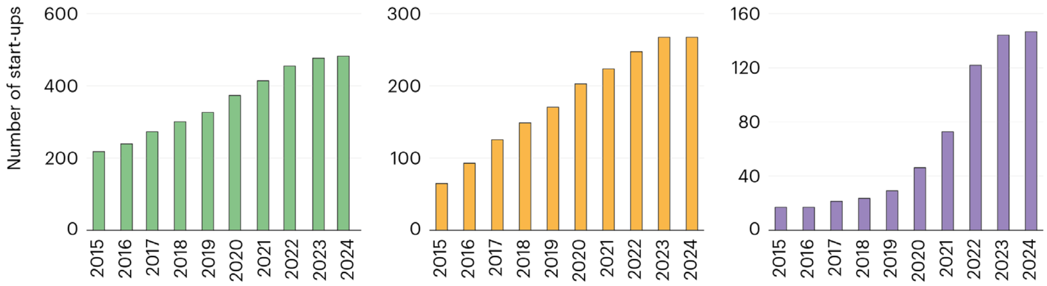


Corporate energy R&D spending has been growing **three times faster** than GDP

Automotive companies now fill 13 spots in the top 20 firms by energy R&D budgets.

Three dynamic areas in focus: battery minerals, AI for energy, and CDR

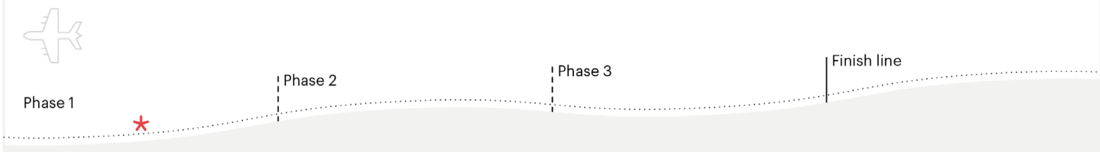
Each sector has unique challenges.



18 "Races to Firsts" will be tracked online by the IEA towards demonstrations of high-potential solutions

Example: First carbon-free flight

A safe continuous flight of 1 000 km or more with no propulsion from a carbon-containing fuel.



* 2024: A US-based company completed a manned 840 km test flight of a hydrogen-powered 4-passenger plane in the United States (TRL 6).

1. Introduction

The unprecedented speed at which the energy system is changing has been enabled in part by technological innovation. In a virtuous cycle, policy support and market forces have helped drive innovators to reduce the costs and raise the quality of energy technologies, thereby spurring more market demand, investment, economies of scale and new business models. In real terms, the installed costs of solar photovoltaics (PV) and lithium-ion batteries are roughly 65% and 85% lower than they were just 10 years ago. The new industries created around these technologies have grown up fast, becoming major players in the global economy. The global market size for solar PV, electric vehicles (EVs) and their batteries has grown nearly sevenfold since 2015 to exceed USD 550 billion, which is around one-third of the annual value of all natural gas produced globally today. Achieving similarly powerful dynamics for a wider range of energy technologies via dependable market demand, competition and pro-innovation policy regimes is the motivating challenge behind this report.

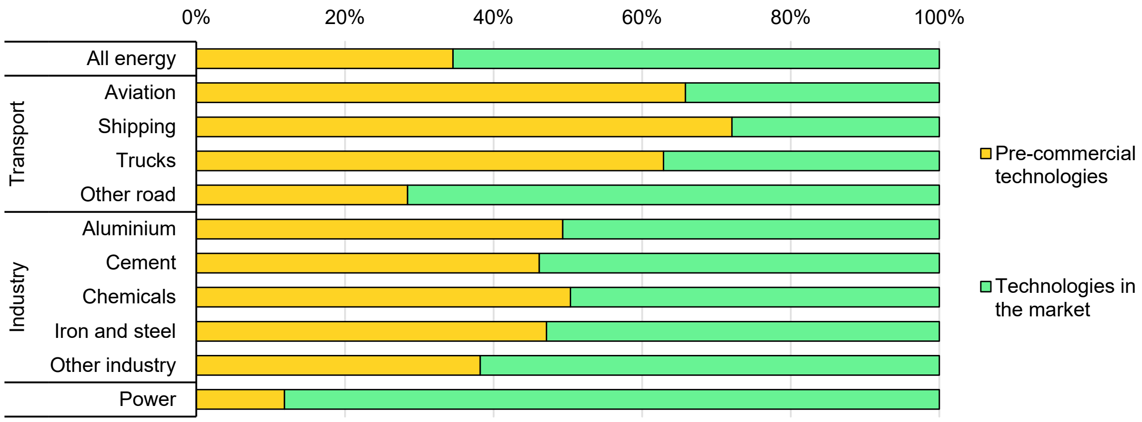
Innovation has long underpinned energy and economic policy objectives

The impacts of technology innovation are evident across all parts of energy supply, distribution and use. For households, they include greater comfort via new systems and software for managing heating and cooling. At the level of countries, impacts are visible at the scale of trade balances. Since 2000, when horizontal drilling and hydraulic fracturing techniques were introduced to the oil and gas industry, the United States has shifted from importing oil and natural gas equivalent to 46% of its demand to exporting oil and natural gas equivalent to around 10% of its demand. Unconventional oil and gas production in the United States is now equivalent to around 90% of US demand, up from 12% in 2000. This revolution in drilling has now begun to spill over into adjacent areas such as geothermal energy and, potentially, geological hydrogen deposits. In the People's Republic of China (hereafter "China"), innovation in batteries and EVs and their manufacturing has reduced costs and improved user experience. This has assisted uptake in a context in which the country imports more than three-quarters of the oil it uses. Having reached a rate of electrification of the road vehicle fleet of 17% in 2024, China's oil imports were 8% lower than if these vehicles had run on gasoline or diesel.

At the formation of the IEA in 1974, international collaboration on technology to reduce the likelihood and severity of future energy shocks was already a foundational pillar. Programmes for undertaking joint research and analysing the implications of R&D progress for energy efficiency, fuel conversion, nuclear energy and renewables have been a part of the IEA framework since the 1970s. This mandate was further bolstered by the 2024 IEA Ministerial Communiqué, which reiterated countries' collective commitment to supporting energy R&D to reach a range of key policy objectives.

As innovation changes the energy landscape, it alters policy makers' key concerns, which in turn steer the direction of R&D. Over the years, the IEA's work on technology innovation has broadened to cover technologies that could spur progress toward IEA Members' shared and diverse policy goals including energy access, air pollution and climate change mitigation. This has drawn attention to key priorities for filling gaps between policy objectives and technology availability. Climate change is one example and, when considering the emissions reductions that would be needed in 2050 in a possible pathway to carbon neutrality globally, the IEA now estimates that 35% rely on technologies not yet demonstrated at commercial scale. The picture varies by sector, however, and the highest needs for more effective technologies are in parts of the transport sector – shipping, aviation and trucks – and heavy industry. In many cases, the core components are already technically proven, but weak demand and investment hold back the learning-by-doing that lowers costs and leads to product refinements.

Share of emissions reductions in the Net Zero Emissions Scenario in 2050 delivered by technologies available on the market in 2023 and pre-commercial in 2023, by sector

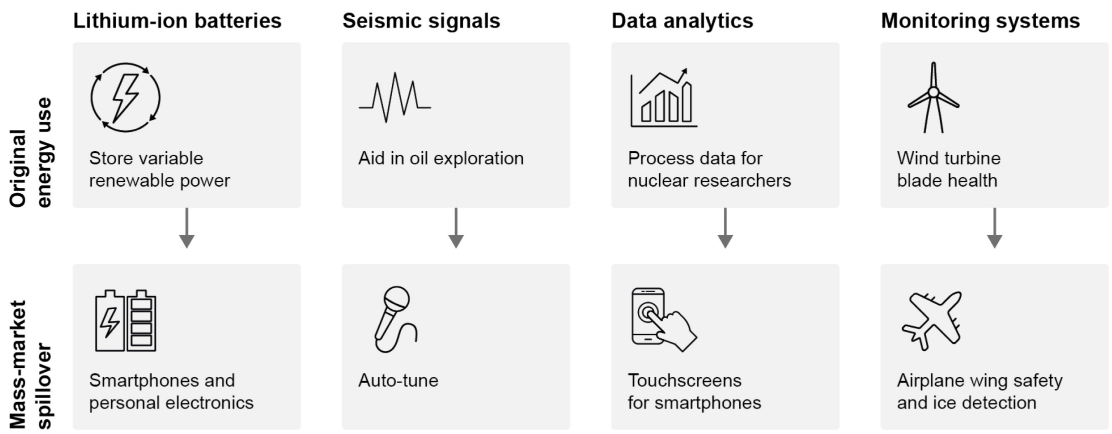


Note: "Pre-commercial" refers to prototype and demonstration stages.
Source: Adapted from IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.

As the major positive impacts of energy technology innovation have become apparent, it has attracted greater policy attention. This has been reinforced by awareness of the importance of innovation to securing countries' competitive positions in key technology supply chains, and the resilience of those supply chains. As explored in the IEA Energy Technology Perspectives 2024 report, rapidly growing energy technology supply chains offer major economic opportunities to advanced, emerging and developing economies alike. Based on policies already in place in 2024, the market for just five energy technologies – EVs (including batteries), electrolysers, heat pumps, solar PV and wind turbines – grows threefold to USD 2.1 trillion by 2035. Technology developers and manufacturers with the most competitive products stand to reap significant rewards, and this will benefit the countries and regions in which they are based.

Energy innovation can also generate good value for taxpayers: reviews of 40 years of a major US energy R&D programme found that the net economic benefits of public R&D spending added up to an annual return on investment of 27%, and a cumulative benefit-to-cost ratio of 33:1.[2] If this were extrapolated to the USD 50 billion of global public energy R&D spending we report in this publication, it would yield over USD 1.6 trillion of economic returns in the future. If the returns accrue, for example, over a 5-year period starting in 2030, the benefits from energy R&D spending in recent years could represent 1.1% of global GDP in the first year alone. Some of these returns are from the commercialisation of energy R&D in non-energy sectors, given that energy R&D has historically been a cornerstone of technology innovation for such high-impact products as smartphones. Not only are such economic impacts accompanied by job creation, but R&D itself is labour-intensive compared with other economic activities and employs highly skilled workers.

Examples of ways in which energy innovation has led to broader economic impacts



Sources: EA analysis based on Oak Ridge National Laboratory; Business Inside (2014), How an oil engineer changed the music industry; Goodenough (2018), How we made the Li-ion rechargeable battery; Klagenfurt University (2018), New technology to determine ice on aircraft.

[2] 33:1 if undiscounted, or 11:1 at a 7% discount rate. The authors provide reasons why these values are likely to be conservative.

The purpose and structure of this report

This report addresses an unmet need for a global stocktake of progress and challenges in energy technology that can inform decision makers from the public and private sectors. Unlike other parts of the energy system, there is currently no authoritative, international reference on the state of energy innovation, covering technological progress, financial trends, and putting policy and innovation “ecosystem” activity in the context of broader energy and climate challenges. This is partly because innovation is inherently difficult to measure. Its impacts can sometimes appear sudden and unanticipated, even by experts that follow it closely. Compared with past decades, a larger share of energy technologies today are modular, mass-manufactured and adopted directly by end-users, which can be a recipe for exponential growth in the right conditions – initial periods of seemingly slow progress followed by steep uptake and disruption of the status quo. Technology innovation has been a key factor in propelling smart meters, heat pumps and induction-based cooking towards such milestones. In heavy industry, the same dynamic may soon emerge for electrolytic processes and new means of delivering high-temperature heat with lower emissions. A range of metrics and horizon-scanning inputs are needed to identify trends and put progress in context.

The report is intended to help inform the global energy innovation agenda for policy makers and other stakeholders, based on a common understanding of where challenges are being successfully tackled and where more attention is needed. In addition to presenting the latest IEA data on key innovation metrics, including finance, the report draws on consultations undertaken by the IEA in late 2024 and early 2025. Notably, it presents perceptions of innovation progress from nearly 300 survey respondents from the research, industry, investment, start-up and policy communities. As a network of experts working on energy technologies, the IEA Technology Collaboration Programmes (TCPs) are without parallel, and their members have contributed many of the insights that illustrate the chapters. Their views on today’s pace of progress are collected here for the first time, alongside the details of recipients of recent TCP awards. Another valuable resource is the deep knowledge of the government and research participants in Mission Innovation (MI), an international initiative dedicated to advancing energy innovation. MI efforts to track policy updates in this area are a precious source of input.

The intergovernmental energy technology innovation landscape

- **IEA Committee on Energy Research and Technology (CERT)**. Since its founding in 1975, CERT has co-ordinated and promoted public R&D and early deployment efforts across all energy technology areas and holds regular focused discussions on emerging technology areas.
- **Mission Innovation (MI)**. An intergovernmental coalition of 23 countries and the European Commission founded in 2015 to co-operate on challenges relating to energy R&D and demonstration, MI co-ordinates seven "missions" in which international teams of R&D experts, many from public institutions, collaborate towards ambitious goals in priority technology areas.
- **IEA Working Parties**. Over the years, the CERT has established five working parties to exchange knowledge among governments on technology developments; they currently relate to Fossil Energy, Renewable Energy Technologies, Energy End-Use Technologies, Fusion Power and Industrial Decarbonisation.
- **IEA Technology Collaboration Programme (TCP)**. The first TCP was founded in the mid-1970s and since then, the programme has grown to encompass 38 autonomous TCPs that each cover a particular energy technology area, drawing national members from research institutes and companies across 53 countries. In total, TCP membership includes over 6 000 experts. The TCPs support IEA technology work and collectively exchange updates at least every 2 years.
- **IEA Experts' Group on R&D Priority-Setting and Evaluation (EGRD)**. Established by the CERT in 1993 to advise governments on energy R&D priorities and evaluation of R&D activities.
- **Technology Mechanism of the United Nations Framework Convention on Climate Change (UNFCCC)**. Established in 2010 to support countries' obligations in relation to R&D, demonstration, deployment, diffusion and transfer of climate change mitigation and adaptation technologies. It consists of a policy arm, the Technology Executive Committee (TEC) and a Climate Technology Centre and Network (CTCN) to facilitate technical capacity building with developing countries.
- **United Nations Climate Change Global Innovation Hub (UGIH)**. Launched in 2021 as a UNFCCC implementation body, the UGIH is overseen by UN governments as a means of holding dialogues about how to bring about radical technological changes to mitigate and adapt to climate change. It has a mandate to give innovators from developing countries access to incentive instruments.
- **United Nations Industrial Development Organization (UNIDO) Global Cleantech Innovation Programme (GCIP)**. Since 2014, the GCIP has connected governments and other parties in 15 emerging and developing economies to support innovation ecosystems, with an aim to foster the creation of over 2 000 new businesses developing or marketing low-emissions energy and other environmentally friendly technologies.

The next chapter of *The State of Energy Innovation* is dedicated to the highlights of the past year. In any given sector it is difficult at times to grasp all the good news stories about promising laboratory results, proofs of new concepts and investment in major new facilities. It is practically impossible to keep track of developments during the year across the whole energy system. Chapter 2 therefore provides a summary of the brightest spots of progress across a broad range of categories related to key stages of innovation and across all technologies relevant to securing affordable and sustainable energy supplies. Notably, it builds upon the unique platform of the IEA Energy Technology Guide, a database of around 600 energy technologies and a reference for tracking their technology readiness levels (TRLs) that the IEA updates every year. Chapters 3 and 4 provide an overview of key metrics related to finance and tracking of energy innovation progress, including R&D spending, venture capital, patents and demonstration projects. In Chapter 5, we turn the focus to some important innovation challenges to help focus decision makers' attention and have selected 18 "races to firsts" to track over the coming years. The following chapter introduces the latest notable policy updates from around the world and some of the key policy challenges identified by stakeholders.

The final chapters of the report each focus on one of three specific technology areas of particular relevance to international deliberations in 2025. They represent emerging areas about which there is significant uncertainty among decision makers about their potential and status, as well as the pace of their potential development. They are also areas that will be prominent in 2025 in the debates of international fora such as the G7, G20, and the MI Ministerial. The three areas are technologies to help diversify mineral inputs to EV batteries, the use of artificial intelligence (AI) to accelerate technology innovation, and carbon dioxide removal.

Technology innovation is one pillar of a coherent approach to today's major energy-related challenges, alongside efforts related to finance, market regulation, energy access and people-centred considerations, and it remains a key driver of economic prosperity. It is a source of inspiration about human ingenuity to rise to the biggest challenges of our times, and a reminder of the strength of collaboration for accelerating the pace of change. Today's investments and project selections will shape the affordability, security and sustainability of energy in the future. We hope that this report can contribute a foundation for sound decision-making on policy design and prioritisation at a time when macro-level trends in society are shaping the energy technology outlook in new ways.

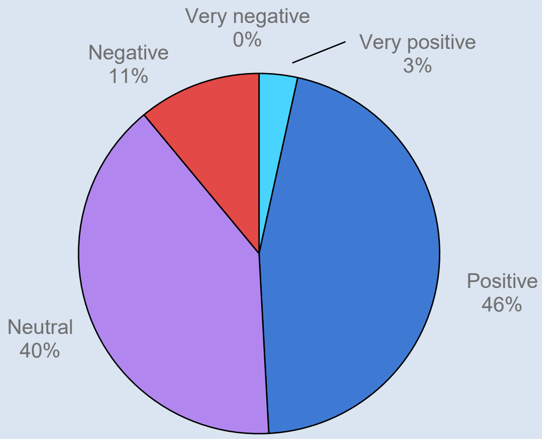
Results of the IEA expert survey for The State of Energy Innovation

Input for this report was gathered through consultation, notably a survey held between December 2024 and January 2025 that received almost 300 responses from representatives across 34 countries and 15 domains of energy technology. The survey was designed to provide a snapshot of innovation experts' insights on progress in 2024 and expectations for 2025. The results relating to innovation highlights, policy updates and priorities have informed the analysis throughout this report.

Questions covered technology highlights, project examples, near-term outlooks, policy practices and strategic priorities. Respondents came from different spheres including policy-making, academic research, corporate R&D, business development and investment. Notably, over 60% of the responses were contributed by experts affiliated with the IEA TCPs and Mission Innovation Missions.

The survey responses indicate a range of sentiments about the state of energy technology innovation and its prospects for the near term. While many respondents cited uncertainties stemming from the complex geopolitical context and fossil fuel price volatility, overall, the results portray a tone of cautious optimism. Respondents were cautious regarding near-term prospects for the United States, whereas for Europe, responses were more varied, with a mix of positive and negative views about the near-term prospects. There was a general sense that energy technology innovation in China, which is proceeding quickly, is somewhat insulated from some of the pressing finance and trade challenges seen elsewhere.

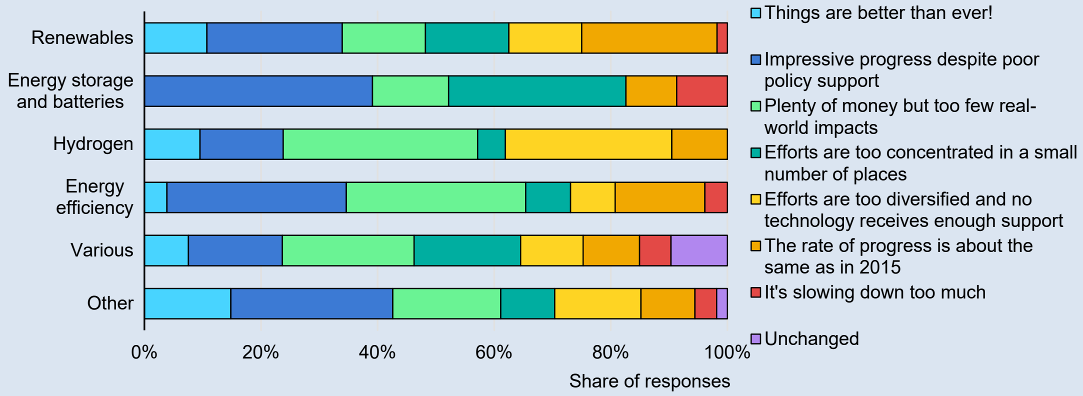
Survey respondents' views of energy technology innovation progress in 2025, compared with 2024



Respondents were in agreement that innovation has gained momentum over recent years, driven by political commitment to technological change in the energy sector and recent energy crises. However, there was recognition that this momentum has not been evenly distributed worldwide, with emerging markets and developing economies not yet sharing in the broader benefits of technology development. Many respondents asserted that policy efforts are still insufficient to meet the scale and urgency of key policy challenges, citing a perceived lack of ambition among both public and private actors and a lack of recognition of the time it takes to turn over the stock of energy technologies in the economy. High cost and risks were commonly referred to as barriers to scale-up, alongside bureaucratic hurdles and outdated infrastructure, such as power networks that require upgrades.

Respondents identified batteries, solar and thermal storage as the areas making the most significant strides in recent years. Moreover, many think that technologies such as solar, batteries and EVs have reached a level of maturity where future progress is increasingly driven by market competition rather than policy support. This points to a shift in the innovation landscape, with policy needed primarily to ensure that innovation ecosystems deliver the continual improvements driving competitiveness. Ocean energy, demand-side response and lignocellulosic biofuels were seen as needing more attention, while perceptions of progress on hydrogen; carbon capture, utilisation and storage (CCUS); geothermal and wind were mixed.

Survey respondents' perceptions of progress on energy technology innovation in the last decade, by sector in which they work



Notes: "Various" refers to responses coming from experts that identified themselves as working across multiple sectors. "Other" includes responses from specialists working on CO_2 removal; carbon capture, utilisation, and storage; critical minerals; heavy industry; nuclear energy; power and grids; and transport.

Most respondents were based in advanced economies, with just 4% of responses from emerging and developing economies. One-third of respondents identified themselves as working across multiple sectors, followed by specialists on renewables (20%), energy storage, efficiency and hydrogen (each around 10%).

Recent macro trends that are set to shape energy innovation

The trends and developments presented in this report are occurring against a changing political and technological backdrop. While it is not possible to catalogue the full range of issues and uncertainties that are influencing energy technology decisions across sectors and countries, nine macro-level trends are described here to help put the report's content in context.

- The intersection of industrial **competitiveness** with energy prices and new energy technologies is a topic of the highest political importance in countries around the world. While the framing of the issue varies – between advanced economies seeking to maintain productivity and quality jobs, and developing economies aiming to attract inward investment and boost prosperity – commitment to innovation and uncertainty about where to invest are common to all countries. This raises the possibility of increased energy R&D budgets and support for innovators but also requires clear communication of the link between R&D and jobs, as well as grounded expectations of the risks and the pace of change.
- Shifts in **geopolitics**, potentially leading towards more fragmentation, represent a challenge for energy innovation, which relies on the exchange of ideas and trade. The prospect of trade conflicts could have significant downsides for the pace of innovation and market uptake, narrowing the outlooks for multinationals and multilateral co-operation. Renewed commitments that make international technology collaboration resilient could reduce uncertainty, for example by deepening co-operation between researchers in alliances of countries that wish to tackle key challenges together. Export restrictions for energy-related technologies have become a new feature of the geopolitical situation, alongside more familiar restrictions on exports of materials. For example, China proposed restrictions on exports of direct lithium extraction and lithium iron phosphate technologies in January 2025. This is a factor that will shape the case for energy innovation and the extent to which international collaboration is possible and encouraged.
- The emergence of **AI** as a new general-purpose technology is, like general-purpose technologies before it, spurring intense competition for technological supremacy between countries and regions. The push by governments to secure AI leadership and support its rapid deployment for economic productivity and defence will doubtless have spillover effects for energy-related innovation. One effect will relate to the discovery of materials via AI-driven R&D. Another could result if automated vehicles, an area that has not yet caught up with the expectations of the 2010s, are deployed more quickly, with uncertain implications for energy demand and the types of batteries and infrastructure that will be most suitable for emergent patterns of vehicle use.
- High expectations and competition for AI are one reason, alongside EV deployment and cooling needs, for a return to **growing electricity demand** projections in many advanced economies. Around the world, planners of

electricity-intensive projects are exploring ways to secure affordable round-the-clock power supplies in a cost-efficient manner, and governments are keen to attract investments in manufacturing and data centres. This expands the case for technology innovation that can bring dependable power supplies online quickly, whether behind-the-meter, large power plants or aggregated decentralised assets.

- Following several years of inflation, **affordability and cost control** are critical considerations for governments. In some regions, investors and funders are actively seeking technology opportunities for mitigating new **risks of energy supply disruptions** – such as wildfires, trade chokepoints or transmission sabotage. Innovators that can address multiple policy priorities will be well-positioned for faster scale-up.
- It has become clearer that innovation progress is unlikely to be a significant barrier to adoption of many key technologies this decade. Despite reaching market maturity, widespread deployment of solar PV, lithium-ion batteries, EVs, wind turbines and other technologies continues to spur innovation, largely through competitive pressures and market uptake. Self-reinforcing feedbacks suggest that **sustained demand will continue to reduce costs and improve performance**, allowing governments to focus their innovation efforts on other bottlenecks. These include the supply of talented scientists and engineers; hard-to-decarbonise sectors; technology or materials gaps that could be barriers to adoption in the 2030s; and supply chain resilience.
- In the past five years, progress towards reducing poverty rates around the world has stalled, notably in sub-Saharan Africa and Latin America. Progress on increasing **energy access has slowed** in these areas, and even gone into reverse in some countries. Yet, at the same time, these countries have tremendous potential to generate large amounts of inexpensive energy, in particular from renewables, and build competitive economies on this foundation. There has been a push to improve access to capital for renewable and other energy sources in emerging and developing economies, based on a rationale of benefits for the international community as a whole. One aspect of this relates to reinvigorating deployment of clean cooking appliances, which has an under-addressed innovation component, while other aspects are about enabling earlier adoption of new technologies in these regions.
- The emergence of more complex manufacturing supply chains for energy technologies (such as those connecting minerals mining with battery production) has revealed new challenges for energy technology investments. Given the outsize role established by China in several of these supply chains, the challenges are intensified for other regions. Minimising environmental and social harm is one aspect. Another is that competitive manufacturing relies on reliable yield, excellent quality control and high speed of production lines, which stem from regional ecosystems of technology providers, component suppliers, innovators and producers. Recent high-profile setbacks for energy technology factories have focused more attention on the role of **manufacturing innovation and the industrial needs for successful scale-up**.

2. Recent developments illustrate progress

Innovation always involves grappling with uncertainty – and the year 2024 was characterised by uncertainty on multiple fronts, reflecting rising geopolitical tensions, anticipation of potential shifts in policy and continued wariness about high financing costs. Against this backdrop, we have compiled key developments from the past year that fired up our optimism about the pace of change in energy technology innovation and the accompanying reductions in costs. The list is not intended to be exhaustive; rather, we aim to showcase progress across a range of technology areas and bring to the attention of decision makers examples of developments that can change perceptions about the potential of new technologies. It draws on the latest update to the ETP Energy Technology Guide, as well as insights collected through a recent survey of technology and innovation experts, including from governments and the private sector. At this mid-point in the decade, the list provides a snapshot of some noteworthy innovations on the cusp of wider impact on the energy system. While they have been selected to reflect the sectoral and geographical diversity of innovation progress, they are only the tip of the iceberg of impressive advances worldwide in 2024. Another 156 highlights gathered for this report are available to explore online. Those highlighted in the chapter below are grouped in five categories:

- **Prominent advances in research and prototyping**: reported results from projects up to technology readiness level (TRL) 5 that push forward the technology frontier in high-potential areas.
- **First-of-a-kind pilot and demo achievements**: milestones reached during the operation at TRL 6 to TRL 9 in real-world conditions of new technology configurations for a given sectoral or regional context.
- **Announced commitments to go to the next level**: news of a firm engagement from investors or project consortia to take a technology from one TRL to the next, typically enabling a final investment decision on a large project that will reduce outstanding technological risks.
- **New products and processes hitting the market**: launch of a product based on a technology that recently reached TRL 9, whether a consumer good, a service or a licensed industrial process.
- **Enhancements to R&D facilities, test sites and innovation support**. announcement that a new R&D facility, test site or other innovation support facility will be established.

Some of the highlights described in the first two categories led to upgrades of the associated global TRLs in the ETP Energy Technology Guide. The chapter begins with a summary of these recent upgrades, which provides a quantifiable overview of where public funding and market forces are spurring progress.

Technology readiness levels (TRL) and the ETP Energy Technology Guide

The ETP Energy Technology Guide is an interactive database on the IEA website that contains information for over 600 technology entries across the whole energy system. For each entry, the guide includes information on the level of maturity and a compilation of development and deployment plans, as well as cost and performance improvement targets and leading players in the field. It is freely available as a resource for governments, investors and funders, and is regularly updated by IEA specialists.

Information on the global level of technology maturity is standardised across technologies using the TRL scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and used in many government agencies since the 1990s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale. The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology now enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4-5), through to testing in the conditions it which it will be deployed (TRL 6). The technology then moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9).

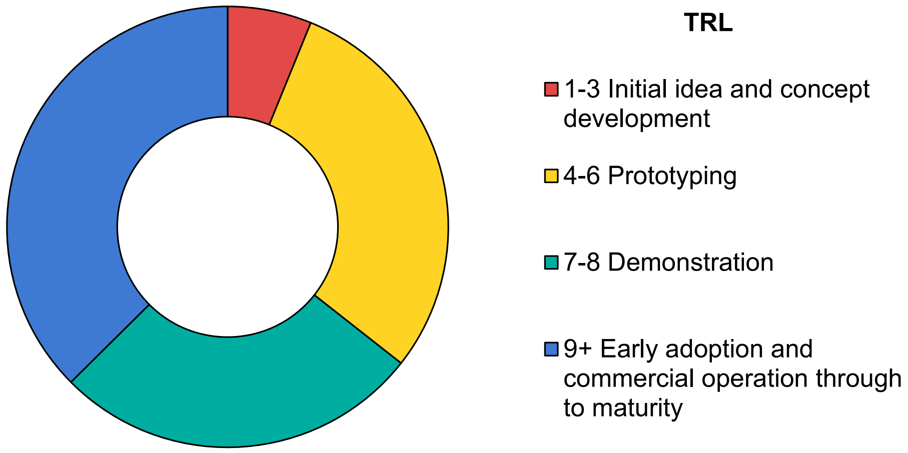
Once a type of technology reaches TRL 9 in the ETP Energy Technology Guide, technology innovation is still necessary. One reason is that, in many cases, the first design to achieve the milestone of a commercial product with minimal technological risk does not go on to become the market leader. Technology designs in the same category at lower TRLs may take longer to reach TRL 9 but ultimately come to have higher performance and lower costs than the pioneering design. While Li-ion electric vehicle (EV) batteries as a class reached TRL 9 in 2009, today's designs have higher energy densities, longer lifetimes and lower prices. Any commercialised product can be expected to continually improve in competitive markets, mostly incrementally but sometimes in surges due to step-changes in manufacturing processes or components. Another reason for continued innovation relates to global penetration – the ETP Energy Technology Guide reflects the global status, but a technology design that can be readily commercialised in one country may need significant refinement before it is fit for another country's geography, climate, regulations and sources of energy.

Beyond the TRL 9 stage, when technological risk has largely been eliminated, considerable effort may be needed from governments, business developers and supply chains to integrate the technology at scale, thus ensuring widespread adoption. The US Department of Energy has developed a parallel Adoption Readiness Level framework to communicate the fact that some technologies may find ready market opportunities as soon as they are technically proven, while others can face a high-risk gap between the two milestones.

Notable upgrades in technology readiness

The ETP Energy Technology Guide is the IEA framework to identify the key technologies for the energy transition and track their development. The guide helps track progress towards the development of technologies that are promoted for their potential to reduce emissions and increase the security and affordability of the energy system. Prior to its publication, many stakeholders lacked a consistent and dependable resource about developments across different energy technology areas.

Energy Technology Guide entries classified by Technology Readiness Level as of the end of 2024

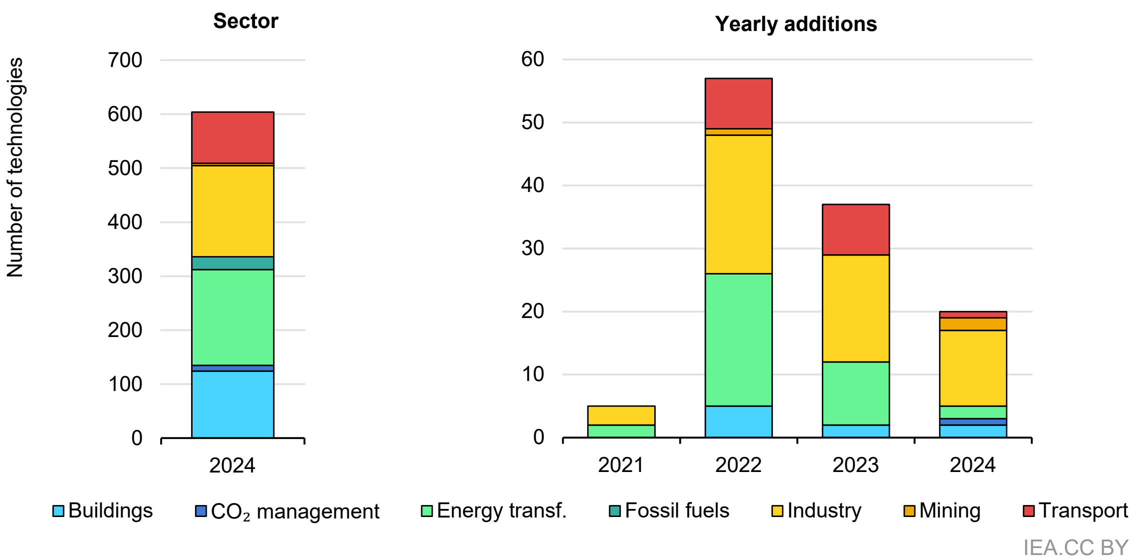


Note: TRL = Technology Readiness Level.
Source: IEA (2024), Clean Energy Technology Guide.

The latest iteration of the Energy Technology Guide contains over 600 individual technologies, with most technologies targeting industry, buildings and transport. The technologies have primarily been identified in the course of IEA analysis, especially its modelling of future energy systems, and also by review of stakeholder submissions. Over the years, we have expanded the number of technologies included – the first edition of the guide, published in 2020, contained 485 entries. As well as the addition of low-TRL technologies as more details about their existence and potential becomes available, some of the expansion relates to the division of higher-TRL technology areas into more specific sub-technologies as these gain traction independently. A relatively small number of entries have TRLs below 4 due to a lack of available information or high levels of uncertainty. Those that are included are typically broader categories that have been used to illustrate future possibilities in IEA modelling exercises.

Throughout the year, we update the TRLs for different technologies as announcements are made or scientific articles are published. Since 2020, on average, 50 technologies have had their TRL updated upwards every year, or roughly 10% of all the technologies we track. This metric goes to show the rapid progress on energy technology development seen over the past 4 years.

Clean Energy Technology Guide entries classified by sector, 2021-2024



Notes: Energy transf. = Energy Transformation.
Source: IEA (2024), Clean Energy Technology Guide.

Prominent advances in research and prototyping

TRL 3
Nuclear fusion
Steady-state high-confinement plasma for nuclear fusion maintained for 20 minutes for the first time.

TRL 3 → 4
Geothermal
Successful tests of competing high-speed geothermal drilling techniques.

TRL 5
Buildings
Solid-state cooling efficiency record broken.

TRL 5 → 6
Road transport / Batteries
Prototype solid-state battery with high energy density and ability to charge in nine minutes.

TRL 4
Road transport / Batteries
First working cell-level prototype of a potassium-ion battery.

TRL 4
Buildings
Landmark test of a low-charge propane heat pump for multi-occupancy buildings.

Note: Country flags represent headquarters of key firms and institutions, as well as project locations, if different.

1. Steady-state high-confinement plasma for nuclear fusion maintained for 20 minutes for the first time

In January 2025, China's Experimental Advanced Superconducting Tokamak sustained a steady-state high-confinement plasma for 1 066 seconds, while France's WEST tokamak reactor sustained plasma for 1 337 seconds just one month later, setting a new world record in nuclear fusion research. These achievements significantly exceed previous records for reactors of this scale and represent important progress towards one key challenge for nuclear fusion energy: maintaining stable plasma conditions. While this development brings the practical use of fusion energy – a technology that promises self-sustaining power and no nuclear waste – closer, many years of R&D and demonstrations still lie ahead if it is to have an impact on the energy system.

2. Successful tests of competing high-speed geothermal drilling techniques

In 2023 and 2024, field and laboratory trials in several countries showed potential to raise geothermal drilling speeds in hard rock, improve efficiencies, lower costs, reduce seismicity-related risks and help unlock previously untapped resources around the world. GA Drilling, a Slovakian firm founded in 2008, successfully tested its downhole drill control system and announced partnerships to trial a pulse plasma drilling head in 2025. HydroVolve, a UK firm founded in 2011, conducted field trials of percussive drilling that achieved record rates of penetration in conventional rock formations. Canopus, a Dutch start-up, reported successful pilot tests of directional steel shot drilling in Switzerland. Researchers in Germany and Switzerland reported promising laboratory results for pulse plasma drilling. Quaise Energy, a US start-up, reported modelling results that bring its millimetre wave energy drilling field trials one step closer. Researchers in France and the United Kingdom reported laboratory tests that confirm aspects of their proposed high-pressure water jetting and percussive drilling approach.

3. Solid-state cooling efficiency record broken

In 2024, Barocal, a UK start-up, developed the first solid cooling system capable of matching the efficiency of traditional vapour compression systems. In parallel, researchers at the School of Engineering of the Hong Kong University of Science and Technology increased the efficiency of elastocaloric cooling multi-material cascade systems by 48% by expanding the temperature window (a critical indicator of a system's ability to transfer heat) to 100 kelvin (K) from less than 50K, which was the highest temperature window achieved using earlier prototypes. Solid-state cooling is a promising alternative to conventional vapour compression air conditioning, heating and refrigeration, which can eliminate the need for hydrofluorocarbon refrigerants. A solid-state cooling system involves caloric materials that, under an electric field (electrocaloric), magnetic field (magnetocaloric), mechanical stress (elastocaloric) or pressure (barocaloric), experience a phase transformation inducing a temperature change.

4. Prototype solid-state battery with high energy density and ability to charge in nine minutes

Samsung, a Korean company with long experience in solid-state batteries, reported a commercial-scale prototype solid-state EV battery cell reaching 500 Wh/kg energy density, significantly higher than the average energy density of today's EV battery cells (for example, lithium nickel manganese cobalt oxide [NMC] chemistry typically has a density of 250-300 Wh/kg). This battery technology has the potential to enable over 950 km range with less than 10 minutes of charging (from 20% to 80%). If such a battery is integrated into EV battery packs successfully, and production scale-up enables their cost reduction to similar levels to today's lithium-ion batteries, these batteries could increase vehicle ranges and hasten the uptake of long-haul electric trucks.

5. First working pre-commercial cell-level prototype of a potassium-ion battery

In 2024, a potassium-ion cell in a large cylindrical cell (18 mm x 65 mm) was produced for the first time by Group1, a US start-up. Proving this technology for EV applications, enhancing key performances like energy density and lifetime, and – if successful – scaling up its production, will require time, but it could become an alternative to lithium-ion batteries for less-demanding applications in the medium term. Together with sodium-ion, potassium-ion could become an additional source of supply chain diversification, strengthening the resilience of the battery market.

6. Landmark test of a low-charge propane heat pump for multi-occupancy buildings

In 2024, Fraunhofer ISE in Germany demonstrated large capacity, low-charge propane (less than 150 g) heat pumps to expand their application to existing multi-family buildings, including floor heating systems and central heating systems. This builds upon the efficiency record set in 2023 for a heat pump for single-family homes with a specific refrigerant charge of around 10 g propane per kW. Due to their high performances, electric heat pumps using low global warming potential (GWP) refrigerants are promising for more efficient and sustainable heating. Propane, a hydrocarbon refrigerant, has a 100-year GWP of 0.02, and can replace commonly used refrigerants with very high GWPs (i.e. a 100-year GWP of over 1000). The downside of propane is its flammability, which is spurring innovation efforts to reduce refrigerant charge.

First-of-a-kind pilot and demo achievements

TRL 6
Solar PV
First demonstration of roll-to-roll manufacturing of perovskite PV at commercial conditions.

TRL 5 → 6
Transport / Hydrogen
World's first use of ammonia as marine fuel on a dual-fuelled ship.

TRL 8
Heat networks / Long-duration energy storage
Commissioning of world's largest underground thermal storage cavern.

TRL 6 → 7
Long-duration energy storage
Commissioning of a 200 MWh long-duration energy storage facility using compressed CO_2.

TRL 7 → 8
Critical minerals / Geothermal
Successful start of production of lithium from geothermal brine.

TRL 8 → 9
Bioenergy
Commissioning of the world's largest cellulosic bioethanol facility.

TRL 6 → 7
Hydrogen
Continuous operation for more than 10 days of a thermo-catalytic pilot plant producing hydrogen and carbon from methane.

TRL 5 → 7
Hydrogen
Ammonia fuel successfully used for 520 hours of power generation co-firing 20% with coal at 1 GW unit.

TRL 6 → 7
CCUS / Cement and concrete
First demonstration at commercial scale of oxyfuel separation of CO_2 in the cement sector.

7. First demonstration of roll-to-roll manufacturing of perovskite PV at commercial conditions

In 2024, scientists in Australia and the United Kingdom demonstrated a high-throughput production process for perovskite solar cells for the first time at ambient conditions, thereby eliminating the need for a complex and expensive production step involving vacuum deposited electrodes. As dependable processes for manufacturing perovskites have been a bottleneck to their industrial scale-up, this brings this next-generation solar PV technology a step closer. Perovskite cells hold the promise of higher conversion efficiency and higher energy density, which means they take up less space for the same power output, and they have a potentially cheaper and less energy-intensive production process. They could also be flexible, allowing a wider range of applications than crystalline silicon. The next steps are to apply the manufacturing techniques to higher-efficiency cells (those demonstrated were 11 percentage points less efficient than typical commercial silicon cells) and improve perovskite durability. As a means of improving module efficiency, perovskites can be added to silicon cells and, in 2024, researchers in China successfully tested such a tandem cell with 34.6% efficiency. Also in 2024, scientists in the United States developed a way to significantly improve the durability of high-efficiency perovskite cells.

8. World's first use of ammonia as marine fuel on a dual-fuelled ship

Australian mining company Fortescue's ship Green Pioneer became the first vessel to use ammonia for marine propulsion in the Port of Singapore in May 2024. The 75-metre-long ship bunkered three tonnes of liquid ammonia, which is a promising low-emissions fuel, and completed manoeuvrability tests. Two retrofitted four-stroke dual-fuel engines powered the vessel with ammonia (at least 30% energy content) and diesel. Meanwhile, engine manufacturers Wärtsilä, WinGD and Hyundai have started offering ammonia engines, and an increasing number of ammonia-powered vessels can be found on order books.

9. Commissioning of world's largest underground thermal storage cavern

Construction preparations started in 2024 for the world's largest seasonal storage facility for thermal energy in Vantaa, Finland. It is designed to hold 90 GWh of thermal energy (as 1.1 million cubic metres of water under pressure at 140 °C), enough to heat a medium-sized Finnish city for a year. This the first time that a project of this scale has been undertaken, and it will provide invaluable experience for other long-duration energy storage projects, especially those enabling different heat sources to charge a single storage facility during a year depending on availability and price.

10. Commissioning of a 200 MWh long-duration energy storage facility using compressed CO_2

In December 2024, Engie, a French electricity supplier, signed an offtake agreement for electricity stored by Energy Dome – an Italian company founded in 2020 – at their 200 MWh (10-hour minimum discharge time) demonstration facility, due to enter service in the first quarter of 2025. This will be the first commercial operation for this type of long-duration storage technology, though agreements to supply similar systems have been signed with utilities in India and the

United States. In 2022, Energy Dome's 2.5 MW (1.6-hour minimum discharge time) plant proved the concept of compressing CO_2 into an above-ground steel container using electrical energy, and then expanding the gas to drive a turbine when off-takers need on-demand power. Long-duration energy storage could help make grids more resilient at high levels of variable renewables and help avoid costly infrastructure upgrades.

11. Successful start of production of lithium from geothermal brine

Vulcan Energy, an Australian company, successfully produced battery-grade lithium hydroxide with lithium extracted from geothermal brine via direct lithium extraction technology (DLE). It is the first geothermal DLE project in Europe and one of the first globally. The company secured offtake agreements with four customers from the automotive and chemical sectors (Stellantis, Renault, LG, and Umicore), which are currently validating the output. It is estimated that the company could produce 8 000 tonnes of lithium per year by 2030, equivalent to 4-5 times Europe's projected supply and nearly 10% of EU EV sales in 2035. A similar project by Controlled Thermal Resources in the United States aims to produce 4 000 tonnes of lithium in 2027, scaling up to 13 000 tonnes per year by 2030.

12. Commissioning of the world's largest cellulosic bioethanol facility

In May 2024, Raizen, a Brazilian company, started commercial production at a plant with the capacity to produce 82 million litres of bioethanol per year from waste cellulosic biomass, the first of its kind at this scale globally. This scale of operation is nearly three times the size of the firm's previous demonstration project (which ran from 2015 to 2024) and its successful operation will confirm the commercial deployment of a technology that has been in development for many years. Unlike bioethanol production from sugarcane juice, which is relatively easily fermented, cellulosic biomass (in this case the fibre and straw left over after the extraction of sugarcane juice) must first be treated to access its sugars. The facility is the first of 20 facilities that are either under construction or planned thanks to an offtake contract with UK oil and gas company Shell. The commercial operation of cellulosic bioethanol production is an important step towards widening the feedstock base that is available for the production of sustainable biofuels and sustainable industrial feedstocks.

13. Continuous operation for more than 10 days of a thermo-catalytic pilot plant producing hydrogen and carbon from methane

The first thermo-catalytic methane pyrolysis demonstration plant was commissioned in 2024 by Hazer, an Australian start-up. It can produce 100 tonnes of hydrogen per year (roughly the output of a 1 MW electrolyser) and 380 tonnes of synthetic graphite. The plant near Perth, Australia, ran uninterrupted for 450 hours. In parallel, Hycamite, a Finnish start-up, is constructing a commercial-scale (2 000 tonnes per year) plant in Finland. Unlike steam reforming of natural gas – the main method of hydrogen production worldwide today – methane pyrolysis splits methane into hydrogen and solid carbon, thereby producing no CO_2 and opening up the possibility of low-emissions hydrogen from natural gas without carbon capture, utilisation and storage (CCUS). In addition, the solid carbon by-product can have some commercial value. In comparison to plasma pyrolysis, which has already been demonstrated at scale, the thermo-catalytic route operates at significantly lower temperatures and uses a simpler reactor design. Technical barriers to scale-up remain, however.

14. Ammonia fuel successfully used for 520 hours of power generation co-firing 20% with coal at 1 GW unit

In April 2024, JERA started a 2-month pre-commercial large-scale demonstration trial to co-fire 20% ammonia at its 1 GW Hekinan coal-fired power plant in Japan. The results of the large-scale trial – which generated power for approximately 520 hours – were positive: the power plant operated comparably to running on coal alone, and no increase in pollutants such as nitrogen oxides (NO_x) levels was observed. JERA now plans to reach continuous operations by 2027 with a 50% co-firing rate. The possibility of combusting high shares of low-emissions ammonia in fossil fuel power plants provides countries with an additional option for cleaner and dispatchable electricity while maintaining service using existing assets.

15. First demonstration at commercial scale of oxyfuel separation of CO_2 in the cement sector

In January 2024, China United Cement Company commissioned an oxyfuel demonstration project that can capture 200 000 tonnes of CO_2 per year from a large cement plant in Qingzhou, Shandong Province. This is the largest CCUS project deployed to date in China's cement sector, and the largest oxyfuel separation project for cement globally. Levels of energy consumption for CO_2 capture that are more than 25% lower than with conventional post-combustion systems are anticipated for this system, opening the possibility of lower costs. This is made possible by the lower energy requirements of vacuum pressure swing adsorption (supplied in this case by PKU Pioneer) for separating CO_2 when it is more concentrated in the exhaust, which outweighs the energy inputs for supplying pure oxygen to the kiln. Another cement-related advance for CCUS was made in 2023 in Canada, when a first-of-a-kind pilot project reported 90% CO_2 capture over 2 400 hours using metal organic frameworks, a promising solid-state approach.

Announced commitments to go to the next level

TRL 7

Nuclear fission

Offtake agreement signed to help nuclear small modular reactor designs reach final investment decision.

TRL 6

Iron and steel / Hydrogen

The largest hydrogen-based direct reduced iron near-zero emissions steel plant achieved financial close.

TRL 4

Cement and concrete

Two new limestone-free technologies for cement production received funding for scale-up to demonstration level.

TRL 8

Industry

Funding secured to build multiple first-of-a-kind plants to electrify industrial heat supply using high-temperature thermal storage.

TRL 6

Geothermal

Funding, offtake and permits secured to bring the world's largest enhanced geothermal project online by 2026.

TRL 7

Ocean energy

Over USD 70 million raised to take a novel 300 kW wave power design to the next stage of demonstration.

16. Offtake agreement signed to help nuclear small modular reactor designs reach final investment decision

US technology company Google signed a contract to buy output from a new nuclear 150 MW_e "pebble-bed" small modular reactor (SMR) design that Kairos Power, a US start-up founded in 2016, hopes to build by 2030, while US e-commerce firm Amazon committed funds to a project feasibility study for US company X-energy's 80 MW_e SMR design (also pebble-bed). The deals reflect the competition for dependable electricity supplies created by expected growth in data centres. In China, the world's second full-size pebble-bed nuclear reactor has been operating at 210 MW_e since 2023, and successfully passed a test in 2024 that demonstrated safe shut-down when disconnected from power inputs, an inherent safety feature of the design. Also in China, the reactor core and reactor building were completed at the first 125 MW_e pressurised water SMR project, which is expected to enter operation in 2026. In Canada, Ontario Power Generation began site preparation and environmental assessments for four 300 MW_e units of GE Hitachi's BWRX-300 design. These developments show practical advances towards commercial SMRs, which have been discussed for many years, as well as regulatory progress, spurred by their potential to support power-hungry digital infrastructure.

17. The largest hydrogen-based direct reduced iron near-zero emissions steel plant achieved financial close

In early 2024, Swedish firm Stegra announced financial close on a commercial-scale hydrogen-based steel plant in Sweden at a level equivalent to USD 7 billion, with nearly two-thirds as debt, and have closed multiple offtake agreements. Direct reduction with low-emissions hydrogen could represent the next-generation technology for making iron and steel. A project of Hebei Bishi in China, and a BLASTR Green Steel project in Finland, among others, are also being pursued as early implementers to achieve megatonne-scale production from 2026. Other technology options for fossil-free steelmaking are being funded at earlier stages by the US, Japanese and Indian governments, and in projects in China, Australia and Namibia.

18. Two new limestone-free technologies for cement production received funding for scale-up to demonstration level

In March 2024, the US government awarded USD 276 million in total to Brimstone and Sublime Systems, two US start-ups, to construct demonstration cement plants that do not use limestone, the source of around two-thirds of the cement industry's CO_2 emissions. Brimstone's process uses silicate raw materials and produces byproducts that have value to the aluminium sector. Sublime's process uses electrolysis rather than heat to produce cement and can also use non-carbonate raw materials. These advances, combined with advances in cement recycling (United Kingdom), lowering the clinker content of cement (France) and CO_2 capture (Norway and China), could help avoid the 6% of global CO_2 emissions for which the cement industry is responsible.

19. Funding secured to build multiple first-of-a-kind plants to electrify industrial heat supply using high-temperature thermal storage

In 2024, Rondo Energy, a US start-up, and Siam Cement Group, a Thai company, began constructing a thermal storage system at hundred-megawatt-hour scale in Thailand in 2024 for use in cement manufacturing. Thermal energy storage can provide baseload heat to industrial facilities, in some cases at high temperatures, enabling the storage of variable renewable electricity and electrification of heat. They are also partnering on expanding production of these systems to 90 GWh per year using the Thai firm's refractory materials (compared with 2.4 GWh per year today). Rondo has agreements for additional projects in Denmark, Germany and Portugal, as well as support from the EU-Catalyst Partnership – a collaboration to package public and private capital between the European Commission, European Investment Bank and Breakthrough Energy, a source of philanthropic and private funds. Also in 2024, Antora, another US start-up, raised USD 150 million to scale up a graphite-based system; Magaldi, an Italian equipment supplier, began construction of an 8.6 MWh sand-based system to start operation at a food processing plant in 2025; and Kraftblock, a German start-up, built a 70 MWh system to replace a 25 MW gas boiler from 2025 onwards.

20. Funding, offtake and permits secured to bring the world's largest enhanced geothermal project online by 2026

In 2024, Fervo Energy, a US start-up, signed a 15-year, 320 MW contract to supply power to a utility, thereby helping to secure a USD 100 million loan for plant construction. The plant is expected to come online by 2026, and follows successful pilot tests since 2023 of drilling techniques that involve hydraulic fracturing, which makes each well 50% cheaper to drill than with conventional methods. Other geothermal innovation projects at similar scales include Geo-Energie Suisse and Geo-Energie Jura's Haute-Sorne project in Switzerland.

21. Over USD 70 million raised to take a novel 300 kW wave power design to the next stage of demonstration

Following successful proof of storm survival and power generation in Portugal, as well as development of a new pre-tension cylinder, Sweden's CorPower Ocean's wave energy converter will now be demonstrated as a 5 MW array of 300 kW units in Ireland, with 2029 as the target for operation. Grant funding from the European Commission has been secured by Simply Blue and ESB, while the technology provider secured USD 33 million in equity investment to facilitate the production of the units. To date, the largest wave energy units tested have been around 1 MW, with none proceeding to deployment in arrays. CorPower's approach uses a cluster of smaller unit size and connects the point absorber buoy to the seabed. Other designs are being validated at test facilities around the world, including the European Marine Energy Centre in the United Kingdom and the US Testing Expertise and Access for Marine Energy Research (TEAMER) programme.

New products and processes hitting the market

TRL
7

Road transport

The world's first megawatt-scale charging point for electric trucks became available.

TRL
9

Energy access /
Clean cooking

Sales began of a gasification-based cookstove with 25% higher efficiency than standard models.

TRL
8

Road transport /
Batteries

Sodium-ion batteries hit the electric vehicle market.

TRL
9

CCUS

First installation of a standardised modular unit for end-of-pipe capture at a scale of 100 000 tonnes of CO_2 per year.

22. The world's first megawatt-scale charging point for electric trucks became available

In May 2024, WattEV, a US start-up founded in 2020, opened an electric truck charging depot with the world's first publicly available megawatt-scale chargers. The three installed chargers can each deliver up to 1.2 MW of power from a system with solar panels and batteries operated in isolation from the grid. New products for megawatt-scale charging began to hit the market soon after the draft specifications for the Megawatt Charging System standard were published. The development of the standard has helped create the market and spurred innovation. Multiple companies are now offering megawatt-scale chargers (Kempower, Power Electronics, Autel, Alpitronic) and compatible trucks (Mercedes-Benz, Tesla), and projects to build megawatt-scale charging networks along freight corridors are underway. Megawatt-scale charging has the potential to reduce the charging times of electric trucks to around 30 minutes.

23. Sales began of a gasification-based cookstove with 25% higher efficiency than standard models

EcoSafi's BetterStove, launched in 2024 at the IEA Summit on Clean Cooking in Africa and developed in Kenya, is a gasification stove that delivers 25% greater efficiency than most other gasifying stoves on the market. It provides up to 2.5 hours of cook time per biomass refill, which is estimated to lead to 50% lower costs than charcoal or liquefied petroleum gas stoves. As it is 95% cleaner than charcoal and meets the World Health Organization (WHO)'s highest emission standards (as monitored by integrated and connected sensors), it has the potential to help the more than 2 billion people worldwide who lack access to clean cooking and suffer the associated negative health impacts.

24. Sodium-ion batteries hit the electric vehicle market

The first cars powered by sodium-ion batteries entered commercial production in China in 2024, renewing interest in the technology, which now boasts additional announced production facilities. Sodium-ion batteries could prove an important source of supply chain diversification, especially at times of high critical mineral prices. Although these batteries cannot yet compete with lithium iron phosphate (LFP) batteries when lithium prices are low, they could become an affordable option for cold climates, where LFP typically performs less well.

25. First installation of a standardised modular unit for end-of-pipe capture at a scale of 100 000 tonnes of CO_2 per year

The largest end-of-pipe modular and standardised capture unit, commercialised by SLB Capturi, was installed in 2024 on a waste incinerator with a capacity to capture 100 000 tonnes of CO_2 per year. The company, a joint venture between US oilfield services company SLB and Norwegian firm Aker Carbon Capture, markets standardised modular capture plants of 100 000 and 400 000 tonnes of CO_2 per year. It is also commissioning the first 400 kilotonne CO_2 per year modular capture unit at the Heidelberg Materials Brevik cement plant, the world's largest capture project on a cement plant, which is scheduled to enter operation in 2025.

Enhancements to R&D facilities, test sites and innovation support

Oil & gas / Geothermal

Several oil and gas majors bring more supercomputing online.

Buildings

Construction began on a groundbreaking new research centre for transforming the buildings and construction industry.

Carbon dioxide removal / CCUS

Commissioning of the world's first open-access direct air capture (DAC) technology test centre, and construction of a second.

26. Several oil and gas majors bring more supercomputing online

Oil and gas companies continue to invest in supercomputing and in 2024 several announcements confirmed that they remain at the forefront of this technology, which they have been active in since the 1950s. ENI, an Italian oil and gas company, commissioned a high-performance 600 petaFLOPS facility to process and interpret large sets of geological data, while TotalEnergies, a French firm, unveiled a different approach by combining a smaller in-house system with advanced cloud computing. Petrobras, a Brazilian oil and gas company, announced an investment to create a 73 petaFLOPS computing centre. Cutting-edge computing can reduce the costs and risks of oil and gas exploration and reservoir management by running complex models, which can also be applied to CCUS techniques, and other low-emissions energy operations.

27. Construction began on a groundbreaking new research centre for transforming the buildings and construction industry

In the second half of 2024, the Living Art of Building, a new research facility, entered construction in Germany. Funded by the German government with the equivalent of over USD 70 million over 5 years, it will focus on design and measurement of new buildings, material use, reuse and recycling for buildings construction. It is expected to welcome over 1 200 scientists in various facilities over several years.

28. Commissioning of the world's first open-access direct air capture (DAC) technology test centre, and construction of a second

In May 2024, a public DAC technology test centre started operation at the National Energy Technology Lab in the United States. Also in 2024, Deep Sky, a Canadian start-up, announced it had started constructing a DAC technology test centre with the goal to remove 3 000 tonnes of CO_2 over 10 years. Access to established infrastructure for testing new carbon dioxide removal technologies at pilot scale can dramatically reduce development costs for technology developers and speed up commercialisation of successful designs.

3. Tracking spending trends

Investment is an early indicator of real-world dynamics: the allocation of capital signals whether energy policies are steering capital to new assets that could displace or outpace the status quo. Investment trends also provide a litmus test of the resilience of different asset types to inflationary or geopolitical pressures. Today, total investments in energy are rising, even as prices fall for renewables, increasing 5% in 2024 compared to the year before. Investments in low-emissions energy have grown to nearly double those of fossil fuels, increasing 7% in 2024.[3]

Both public and corporate energy R&D spending are also trending upwards, increasing 5% and 6% in 2023, respectively, and there are early indications of continued growth in 2024. This is despite the headwinds of higher interest rates and tighter government budgets. Although the pace of growth has slowed slightly since 2022, the momentum of investing in low-emissions energy technologies has been maintained – driven in large part by governments' prioritisation of energy as a key sector for competitiveness and climate policy goals, which has spurred higher corporate R&D in energy-related technologies. We anticipate that 2024 data will confirm the ongoing growth trend.

By contrast, venture capital (VC) investments in energy start-ups responded more strongly to inflationary macroeconomic conditions and policy uncertainty, declining by 23% in 2024. While this follows trends in non-energy technology areas, reflecting the cyclical nature of VC markets, the dip in energy-related VC is more pronounced than other sectors, especially artificial intelligence (AI), which attracted a much higher share of the global VC total in 2024. While bright spots exist in technology areas such as new energy storage options, nuclear and carbon capture, utilisation and storage (CCUS), the recent trend should be of concern to policy makers. It could have long-term negative impacts as innovators struggle to scale up high-potential technologies without access to affordable capital.

Looking further ahead, tracking investment in technology innovation can indicate earlier-stage trends that will shape the energy system of the 2040s and 2050s. The three metrics examined in this chapter – public spending, corporate spending and venture capital – are among the only indicators of innovation effort for which consistent data are available over many years. We consider each of these three metrics in turn, as well as the new sources of finance emerging to support innovative energy technologies.

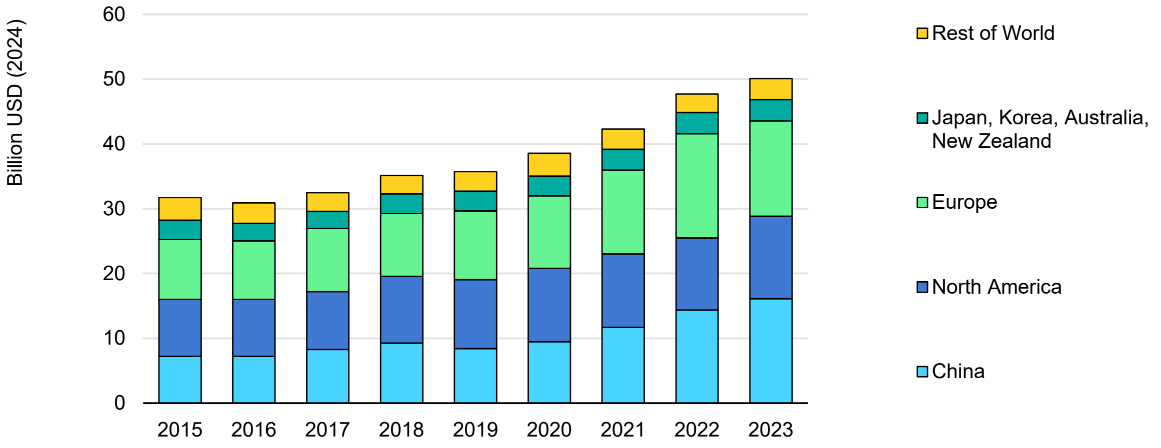
[3] Low-emissions energy investment includes renewable power, grids and storage, energy efficiency and end-use, nuclear and other clean power and low-emission fuels.

Public R&D

Government spending on energy R&D continues to rise. It reached a global total of USD 50 billion in 2023 – 5% up on the previous year – and budget estimates that are already available for 11 IEA Member countries indicate continued growth in 2024.[4] However, the 2024 growth rate for most of these 11 countries is expected to be below 5% – including around 1% or less for Canada and the United States – potentially signalling a slowdown. On the other hand, the global aggregate could be buoyed by a significant annual increase in Japan's Green Transformation initiative budget, largely focused on boosting competitiveness in battery technologies. Though smaller in magnitude, Norway reports a significant increase in renewable energy and hydrogen R&D spending.

In general, public spending on energy R&D is a policy priority for advanced economies working towards their stated ambitions to promote affordable, secure, cleaner energy. Growth is also being spurred by rising interest among governments in supporting domestic competitiveness in emerging energy technology markets. In recent years, the share of low-emissions energy R&D spending has remained at roughly four-fifths of the global total.

Government spending on energy R&D, 2015-2023



Notes: Includes spending on demonstration projects (i.e. RD&D) wherever reported by governments as defined in IEA documentation. State-owned enterprise funds comprise a significant share of the Chinese total. China's 2023 estimate is based on reported company spending where available. The IEA Secretariat has estimated US data from public sources.
Source: IEA (2024), Energy Technology RD&D Budgets: Overview.

In 2023, growth was primarily led by China, with contributions from its major state-owned enterprises, and by the United States, where government investment in

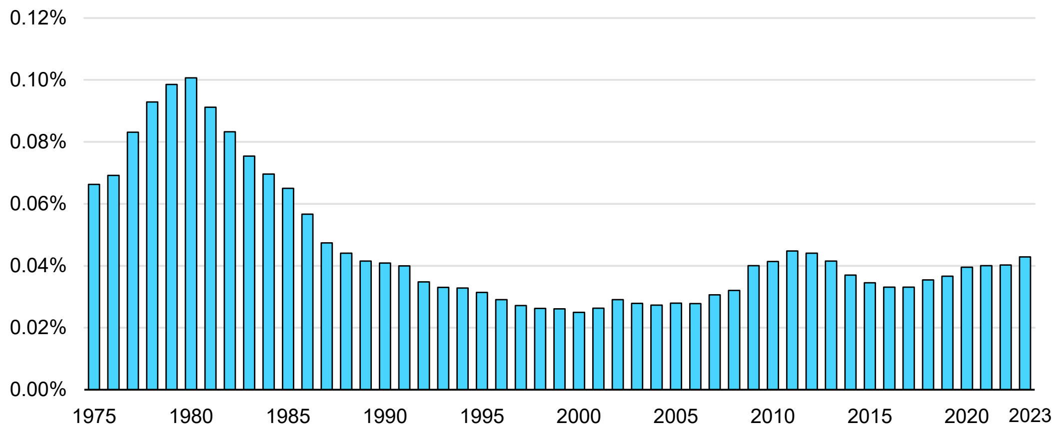
[4] In this Chapter, the term R&D is used throughout for convenience and includes demonstration. In this section, the trends described derive from the IEA RD&D budget database. The IEA has maintained this unique database of government energy RD&D spending since the 1970s. Annual data are gathered from governments in IEA Member and non-member countries with support from Mission Innovation. The annual cycle for gathering 2024 data is not yet complete at the time of writing. Data for 2024 will be published in full in May 2025 and updated in October 2025 on the IEA website.

energy R&D rose by 14%. Both countries have stated ambitions to boost innovation in priority energy technologies in the coming years. While some US financial support to large-scale demonstration projects may not be maintained at current levels, it is the budgeted grant funding for such projects that is included in our dataset, for example for CCUS projects. Whether projects proceed to spending this allocated budget depends largely on how the broader market context for their products, such as low-emission hydrogen, evolves.

In contrast, public investment in energy R&D in Europe decreased 8% in 2023, following several years of notable growth. The largest year-on-year decrease was seen in Estonia, while the absolute value invested in public energy R&D declined most in the Netherlands and in Germany. Public spending on energy R&D in the rest of the world, including emerging and developing economies, rose in 2023. However, this still only accounted for 6% of the global total, with spending concentrated in a small number of G20 countries.

Total public spending on energy R&D per unit of GDP has declined notably since the 1980s, when there was a major push for technological innovation – especially within the nuclear sector – to boost energy security after the oil crisis. Today, there are new and emerging risks to energy security to add to traditional risks to oil and gas security, but spending on R&D per unit of GDP is far lower than the heights of the 1980s, despite a small increase since 2018. In a few countries, including France, Norway and Spain, public spending on energy R&D is close to 0.1% of the total GDP. Since 2021, Spain has notably increased the share of energy R&D spending, as has France, while Norway has historically maintained a high level of R&D investment relative to GDP.

IEA Member country public spending on energy R&D as a share of GDP, 1975-2023



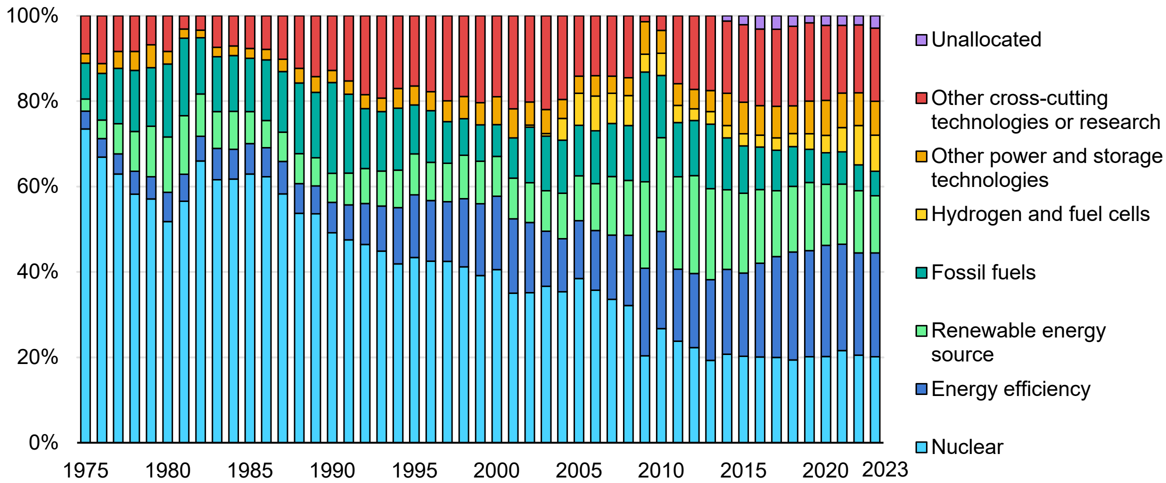
Notes: The data for Estonia and Lithuania begin from 1993 and 1992. The chart does not include Latvia, which became a Member of the IEA in 2024. The relevant parts of the American Recovery and Reinvestment Act budget of 2009 are distributed over the 5 following years.
Source: IEA (2024), Energy Technology RD&D Budgets: Overview

Ten highest average public energy R&D spenders as a share of GDP among IEA Member countries, 2021-2023

Country	Average public energy R&D as a share of GDP, 2021-2023	Average GDP, 2021-2023 (billion USD)
Norway	0.10%	479
France	0.09%	3 004
Spain	0.08%	1 562
Belgium	0.06%	621
Finland	0.06%	297
Canada	0.06%	2 099
Austria	0.06%	512
Japan	0.06%	4 158
Sweden	0.05%	583
United Kingdom	0.04%	3 323

The focus for public spending on energy R&D has also evolved over time and become increasingly diverse, targeting multiple technologies across sectors. While the share of nuclear has fallen from 76% in 1974 to 20% in 2023, the largest share in 2023 was directed to energy efficiency (24%), which includes vehicles and their batteries. The analysis is impeded by the growing classification of research projects as cross-cutting, which lacks specificity regarding the distribution of R&D efforts across different areas.[5]

Evolution of public R&D budget per year with technology shares, 1975-2023



Notes: Other power and storage category includes non-transport energy storage applications and energy efficiency includes vehicle batteries and storage technologies. For definitions of the technology categories, see the IEA Guide to Reporting Energy RD&D Budgets/Expenditures Statistics.

[5] An ongoing IEA project seeks to revise the technology classification to address imprecise allocation issues and include important emerging technology areas within the scope by 2026.

Corporate R&D

Corporate spending on energy R&D continues to rise, reaching over USD 160 billion in 2023, as companies seek to shore up their competitive advantages in rapidly evolving technologies. On average, corporate spending on energy R&D has increased 7% per year since 2019 – growing at around the same pace as public spending on energy R&D and faster than global GDP over the same period.[6] Initial estimates for 2024, however, indicate slowing growth.

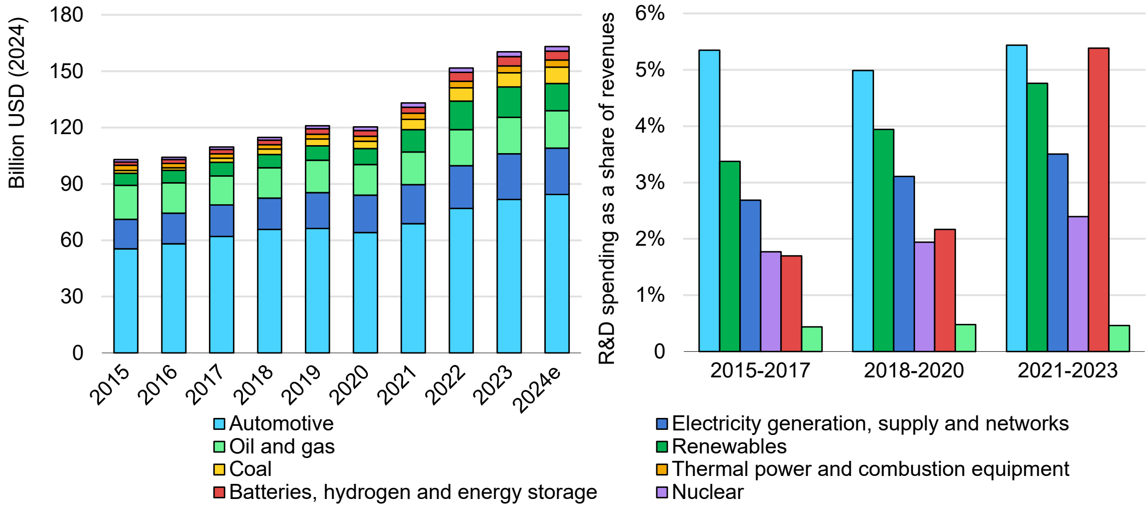
The automotive sector dominates spending on R&D, although all sectors saw an increase in spending in 2023. Thirteen of the top 20 energy-related corporate R&D spenders are automotive companies located in Germany, Japan, the United States, China and the Netherlands. For example, Volkswagen and Mercedes-Benz increased their total R&D spending by a combined USD 5.5 billion, or 19%, while electric vehicle manufacturers BYD and Tesla were the thirteenth and fourteenth largest spenders, respectively. In some cases, increased R&D spending by automotive manufacturers and their suppliers also reflects the counter-cyclical government support, such as public loans, that has been directed to low-emissions technologies in recent years.

At the regional level, global corporate energy R&D spending has been boosted by Chinese firms, which have allocated increasing sums to R&D as their balance sheets have grown. Chinese corporate energy R&D spending has risen from around USD 18 billion in 2015 to over USD 62 billion in 2023. Three Chinese state-owned energy companies – PowerChina (power plant engineering), PetroChina (oil and gas) and State Grid Corporation (electricity networks) – now rank among the top ten largest corporate energy R&D spenders globally.

Spending on R&D has remained elevated in several corporate sectors that have been under pressure to develop low-emissions technology solutions. This can be seen by looking at the total R&D spending by firms in sectors whose emissions are considered more difficult to abate (rather than the estimate of their energy R&D spending, shown above). These include the truck, cement and iron and steel industries, whose R&D spending has grown markedly in aggregate since 2021. By contrast, there was less noticeable growth in R&D spending by aviation, rail and shipping companies.

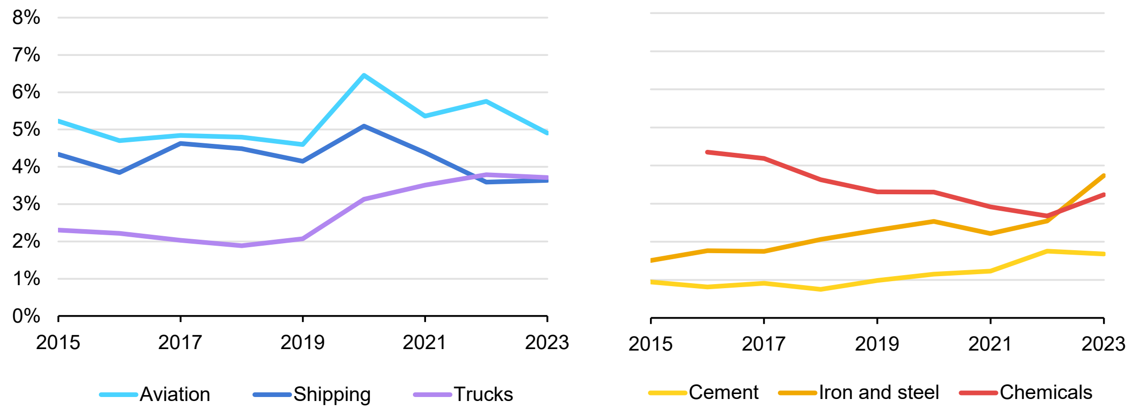
[6] Annual data are gathered from companies' financial reports. The 2024 data is not yet available, as the annual financial reports of companies had not been published by the time analysis was carried out.

Spending on energy R&D by listed companies (left), 2015-2024 and R&D budgets as a share of revenue by sector of activity (right), 2015-2023



Notes: 2024e = estimated values for 2024. Includes only publicly reported R&D expenditure by companies active in sectors that are dependent on energy technologies, including energy efficiency technologies where possible, and based on the Bloomberg Industry Classification System. Automotive includes technologies for fuel economy, alternative fuels and alternative drivetrains. To allocate R&D spending for companies active in multiple sectors, shares of revenue per sector are used in the absence of other information. Values may include both capitalised and non-capitalised costs, including for product development. Right-hand figure considers the top 20 companies earning more than half of their revenues in the sector.
Source: IEA analysis based on data from Bloomberg (2025).

R&D spending as a share of revenue by globally listed companies in heavy and long-distance transport (left) and industry (right) by activity, 2015-2023



Notes: Figure considers the top 20 companies earning more than half of their revenues in the sector. Due to data gaps spending by the chemicals industry is only presented from 2016 onwards.
Source: IEA analysis based on data from Bloomberg (2025).

Venture capital investments

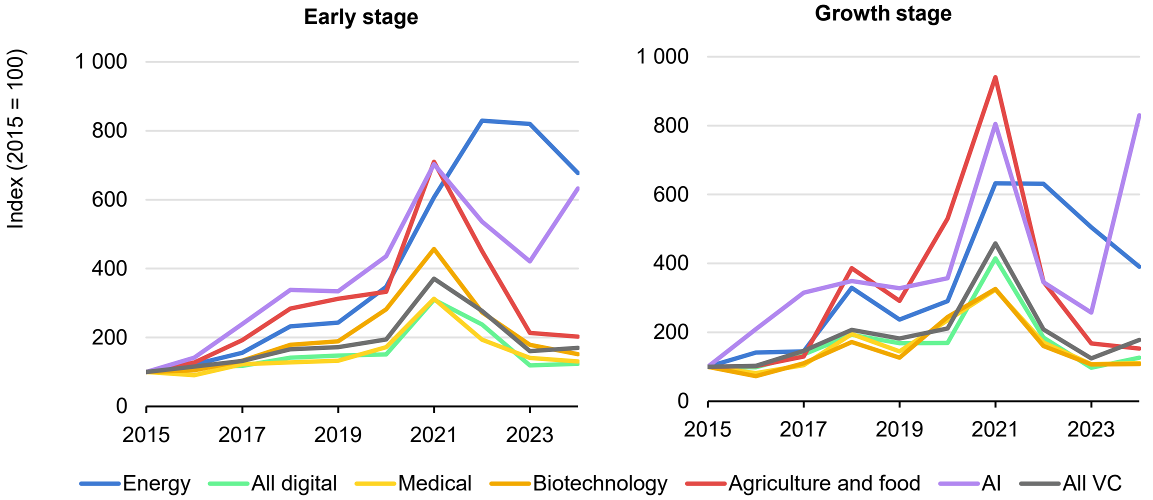
In 2024, venture capital (VC) investments in energy-related start-ups totalled to almost USD 27 billion, a discouraging 23% decline from 2023 levels, which were already lower than the previous year by a similar amount. Early-stage funding decreased by 17%, the first significant year-on-year reduction since 2014. This funding supports entrepreneurs with technology testing and design and plays a critical role in honing good ideas and adapting them to market opportunities. Growth-stage funding, which needs more capital but funds less risky innovation steps, fell by 23%. Growth-stage funding is important for bringing the most promising products to commercial success, and its stagnation could delay how quickly technologies cross the "valley of death" and achieve competitiveness. The 2024 trend indicates that, despite a promising start to the year – with a level of dealmaking in the first quarter that led us to predict modest growth for 2024 – the investment environment has not regained the hoped-for momentum.

Despite the regulated and concentrated nature of traditional energy businesses, there has been a trend in the past decade towards more energy-related technologies being developed within start-ups. One reason is that the landscape of energy technologies has come to include more mass-manufactured technologies, such as batteries, that can scale up relatively quickly from niche to mass markets. Another is that many new technology ideas are a poor fit with the capabilities of incumbents, for whom in-house development of a virtual power plant or a long-duration energy storage battery business would represent a sizeable risk and opportunity cost. However, the sharp rise in energy-related VC activity from 2018 was also fuelled by a low interest rate environment that favoured risk-taking, leading to VC investments in start-ups with the types of hardware technologies that have traditionally been considered a poor fit with VC funding, due to having development timelines of 10 years or more.

The ongoing advance of VC into longer lead-time areas of energy technology scale-up – such as CCUS, geothermal, nuclear and power grid transformers – reflects greater understanding of the energy sector among investors and, for some of them, more patience for financial returns. After the unprecedented flow of VC capital to energy technologies in 2021 and 2022, and the subsequent restraint, a "new normal" may emerge that can guide investors' risk appetite and entrepreneurs' expectations. For some technologies, equity funding will need to be complemented by more support from large corporate partners. Nonetheless, if only a small fraction of the 1 850 energy start-ups that raised VC funding in 2021-2022 meet their scale-up goals, their combined impact on energy by the 2030s could be very significant.

To a large extent, energy VC is suffering from a wider malaise affecting VC, as global macroeconomics, including high interest rates, hinder private equity investments. To some extent, the policy-led nature of low-emissions energy VC helped it weather the impacts of the global pandemic better than other VC segments, with early-stage energy VC peaking in 2022, compared with 2021 for VC overall. Now, however, it is AI that is the outlier, having grown substantially in 2024. The rush of funds in that highly competitive and fast-growing sector may even have drawn capital away from energy technologies. At a time when capital is more costly, the shorter timescales to get a digital technology to market are very attractive. Further analysis of VC investment at the intersection of energy and AI technologies are reported in our special report on Energy & AI.

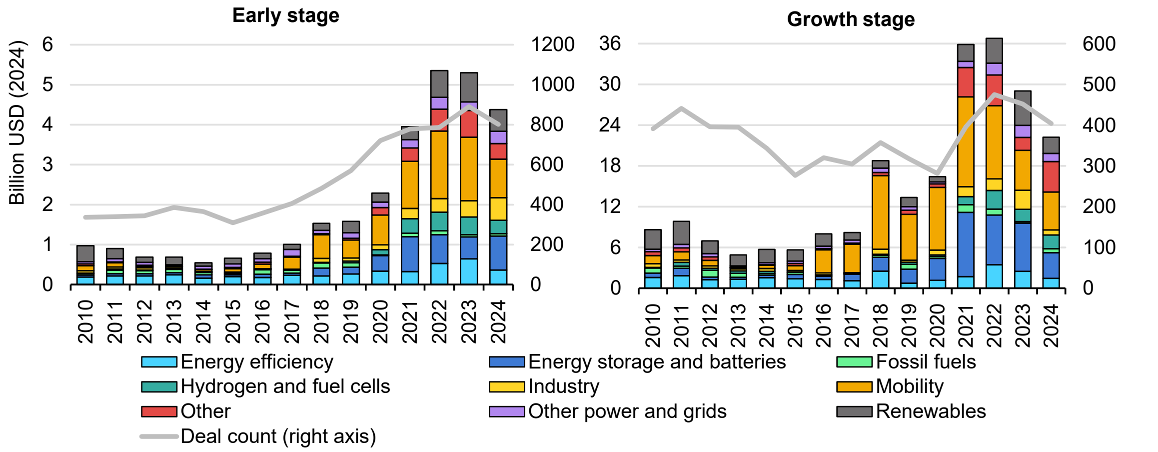
Global venture capital investment by start-up sector, 2015-2024



Notes: AI= artificial intelligence; VC = venture capital.
Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

While VC markets tend to respond quickly to macroeconomic conditions, some factors are more specific to energy. Geopolitics and uncertainties about political commitment to climate-related policies in some countries have raised concerns among investors about future market demand, leading to a “wait-and-see” approach to investment. Some technology areas, such as electric vehicles (EVs) and lithium-ion batteries, are attracting less VC investment because of industrial consolidation that makes market entry harder for prospective new entrants. Nonetheless, the unwelcome drop in energy-related VC is concerning. There is a significant risk that high-potential new technologies could fail to become competitive, or have their market entry delayed by many years, due to a lack of operating capital for their owners. In 2024, deal sizes declined by 11% on average, to USD 8 million for early-stage and to USD 87 million for growth-stage deals, which can act as a brake on progress or lead projects to be cancelled.

Venture capital investment in energy start-ups, by technology area, for early-stage and growth-stage deals, 2010-2024



Notes: Deal count includes deals for which no value has been reported, meaning that the average deal value cannot be accurately derived from the chart. Industry includes start-ups developing alternative pathways to materials. Mobility includes technologies specific to alternative powertrains, their infrastructure and vehicles, but not generic shared mobility, logistics or autonomous vehicles. Other includes carbon capture, utilisation and storage (CCUS), carbon dioxide removal (CDR), nuclear, critical minerals and heat generation. Fossil fuels covers start-ups which aim to make fossil fuel production and use more efficient or less polluting.

Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

A healthy energy innovation ecosystem that can support the major energy security and sustainability goals is one that exhibits steady aggregate VC funding growth and dynamic evolution of the underlying technology areas. The VC trends in 2023 and 2024 are reminders that growth is not guaranteed. Policy support may be needed to help the wealth of emerging technology ideas stay on track through downturns and bridge the gap from research institutions to markets in an ever-wider range of countries.

Not all energy technology areas experienced declines in 2024. The bright spots were among technologies where strong technological competition and untapped near-term market opportunities are clear. The total value of early-stage investments in energy storage and batteries increased more than 50%, after 2 years of consecutive declines. The largest year-on-year increase in the sector was seen in early-stage deals in Europe and North America. Underpinning this was the shift of VC funding from start-ups developing lithium-ion batteries to those developing more novel battery chemistries and battery recycling (see Chapter 7). The value of all early-stage investments in start-ups working on heavy industry applications rose over 40% in 2024. Among growth-stage deals, start-ups working on synthetic fuels, nuclear and CCUS or “novel CDR” attracted around 420%, 240% and 80% more VC, respectively.

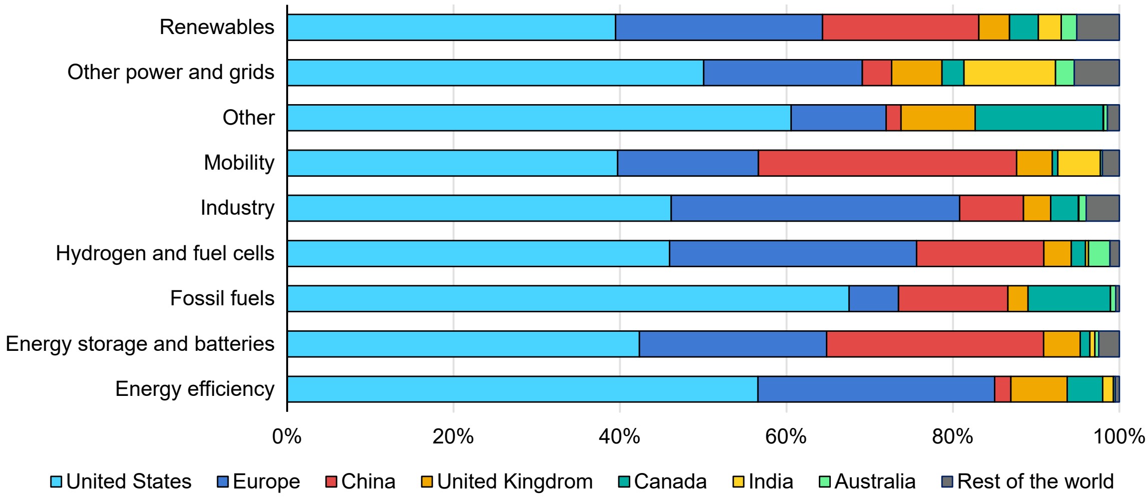
Technology areas with the highest declines in VC funding in 2024 included those with the largest changes toward lower near-term market certainty and those where early deployment and competition are giving way to consolidated, mature sectors. The latter includes EVs, while the former includes hydrogen and fuel cells, for which early-stage VC value declined in 2024. On the other hand, growth-stage dealmaking in the area of hydrogen stayed at roughly the same level, suggesting that start-ups with contracts for supplying major projects are being backed to scale up their supply chains. Solar PV, an area that saw significant growth in 2023, based largely on higher expectations for next-generation materials, raised less than half as much VC in 2024. Given recent progress with perovskite PV (see Chapter 2) this may simply indicate that the sector is relatively shallow, with a small number of firms all raising money in one year and not needing to fundraise again the next year. However, it could be a consequence of the broader withdrawal of capital from energy VC and therefore a cause for concern for this promising technology area that is just breaking out of the laboratory.

The largest deals in 2024 were spread across several technology areas. AVATR, a Chinese electric car maker, secured USD 1.5 billion in growth-stage equity, while Pacific Fusion, a US developer of a pulsed magnetic inertial fusion approach that was founded in 2023 with ties to government laboratories, raised USD 0.9 billion. Among large early-stage deals, Energy Park, a UK EV charging technology developer, closed a USD 44 million deal, and Again Bio, a Danish developer of atmospheric CO_2-to-chemicals technology, secured USD 43 million.

Start-up fundraising by region

In the past 5 years, energy-related start-ups based in the United States have raised more than those in other regions, and most of their capital has come from US-based investors. While China, Europe and the United Kingdom have increased their share over time, there was no notable growth in 2024. As a result, the share of investments in the United States increased to 46%, higher than the 30% in 2023, when more funding was raised in Europe and China. Venture capital from emerging and developing economies (excluding China) decreased around 60% in 2024 compared to the previous year, and their share in the global picture remains small at 4%.

Early- and growth-stage investments in energy start-ups by region and technology area, 2020-2024

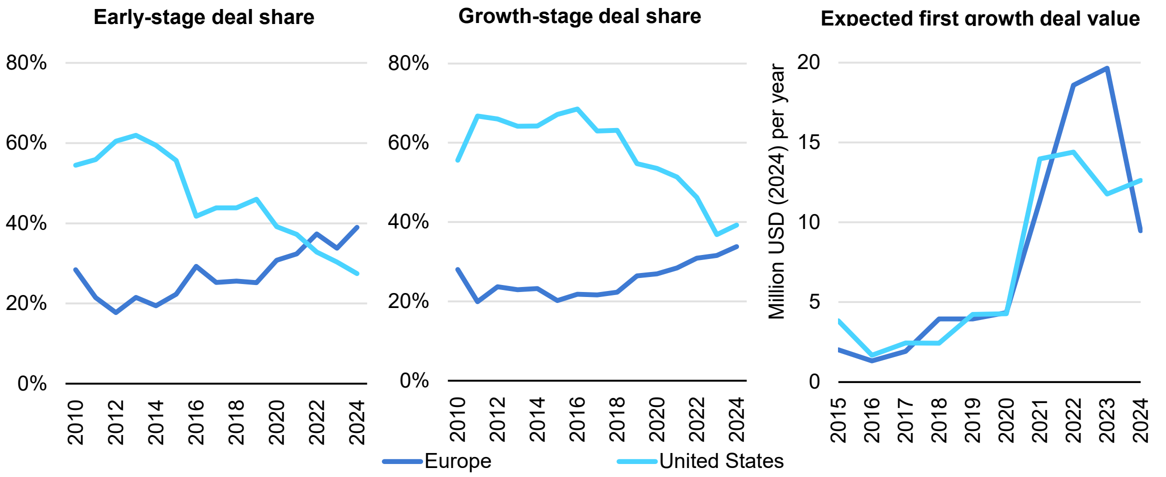


Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

The United States is not only the largest VC market overall, but US-based start-ups in most individual energy technology areas also raise more money than their counterparts in other regions. Chinese start-ups are more concentrated in sectors such as mobility, where they accounted for over 30% of the global value of VC deals from 2022 to 2024. While around half of the deal value in China in this period related to mobility, a further 29% was in the associated area of energy storage and batteries. India's funding has also been concentrated around mobility, which accounted for 60% of fundraising by Indian energy-related start-ups from 2022 to 2024. Europe's activity is distributed more broadly across categories, but it shows notable strengths in relation to applications for heavy industry, energy efficiency and hydrogen and fuel cells.

European policy makers have in recent years been concerned with trying to ensure that more early-stage deals translate into successful growth-stage companies, a metric for which the United States has traditionally performed better. Since 2020, European start-ups have raised more early-stage deals and funding compared with those in the United States. To explore the perception that US start-ups raise more follow-on funding to scale up than their European counterparts, we developed an "expected first growth deal value" indicator to represent how much money energy-related start-ups are raising in their first growth-stage deals, annualised over the period since their last deals. Since 2015, US start-ups have not noticeably outperformed European start-ups by this metric of speed and scale of scale-up funding. Both regions experienced a dramatic increase in this value as deals grew and interest rates were low up to 2022. In 2022-2023, European start-ups even outperformed their US-based peers but, while the United States maintained a relatively steady level in 2024, Europe declined noticeably. This indicates a relative weakening of Europe's ability to convert early-stage VC to growth-stage companies.

Early- and growth-stage energy venture capital deal counts in the United States and Europe as shares of the global total, and expected first growth deal value, 2010-2024



Notes: Expected first growth deal value is a metric that represents the average annualised growth-stage equity raised after a start-up's last early-stage deal until its first growth-stage deal, calculated as the mean of all first growth-stage deals of known value for energy-related start-ups in the given year divided by the number of years since their previous deal, multiplied by the share of start-ups raising funds in the previous five years (to represent the likelihood of successful fundraising).
Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

Start-up fundraising insights by technology area

Venture capital for energy start-ups is distributed among different technology areas and the year-to-year shifts demonstrate the dynamic landscape of energy technology start-ups, as well as the regional differences. Since the 2022 highs, the largest decline has been observed in mobility, energy storage and energy efficiency – the fastest-growing sectors in previous years.

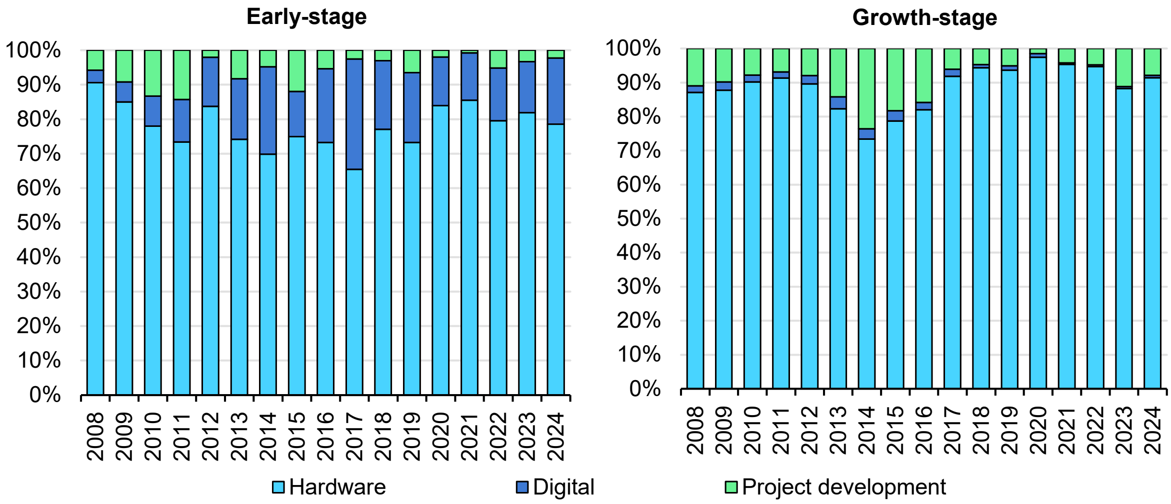
- Collectively, **carbon capture, utilisation and storage** (CCUS) and "**novel CDR**" technologies, grew by 50% compared to 2023, largely driven by **direct air capture** (DAC) (see Chapter 9). Heirloom, a DAC technology provider from the United States, raised USD 150 million.
- **Geothermal energy** saw a 40% increase in 2024, continuing similar growth in 2023, indicating strengthening expectations for this dispatchable, low-emissions energy source. Fervo Energy, a **US** enhanced geothermal firm, raised USD 379 million in growth-stage equity deals and Baseload Capital, a **Swedish** geothermal financing start-up, raised USD 58 million in 2024.
- **Nuclear** total deal value surged by 170% with **fusion** commanding nearly two-thirds of nuclear venture capital in 2024. **Small modular reactors** (SMRs) for nuclear fission accounted for a more modest 6% of the total in deal value.

- Funding for **industrial heat technology** increased over 270% in 2024, making it the only notable growth area for heavy industry. AtmosZero, a **US** company that develops industrial-scale heat pumps, raised USD 21 million. Meanwhile, **thermal storage for industry** increased roughly a third, driven by large deals like USD 150 million secured by Antora, a US start-up developing high-temperature heat storage approaches.
- **District heat**-related start-ups bucked the declining venture capital trend in 2024. Deep Green, a **UK**-based project developer aiming to use data centre heat for district heating, raised USD 255 million, while two **Finnish** thermal storage developers for district heat, TheStorage and Polar Night Energy, raised early-stage funding worth USD 1 million and USD 8.3 million, respectively.
- Non-hydrogen-based **synthetic fuels** experienced a growth in venture capital investments despite having only a small number of deals. **UK**-based Circtec, developing a pyrolysis technology for end-of-life tyre recycling, closed a USD 163 million growth-stage deal.
- Electricity grid flexibility technologies, such as **virtual power plants** and **distributed energy resource management systems**, saw investment growth of 130% in 2024. Flower, a **Swedish** energy asset forecasting, optimisation and trading software provider, secured USD 49 million.
- Other emerging hardware and materials technologies for **power grids** – like **wireless power transfer** – also saw growth. Aeterlink, a **Japanese** developer of long-range wireless power transmission technologies, raised USD 14 million.
- Energy efficiency VC accelerated in **Australia** and **Japan**, particularly for **building energy management systems** and **data centres**. In the **United States**, Ambiq Micro, developer of an energy-efficient microcontroller, raised USD 89 million.
- **Hydrogen-related** investments surged in **Europe** and **Japan**, albeit from a low base for the latter. Tsubame BHB, a **Japanese** developer of ammonia production, secured USD 35 million to scale production. Sunfire, a **German** electrolyser-maker secured USD 234 million, the largest deal in the segment.
- **Renewable energy** investments declined overall but grew in **biogases, wind, geothermal and ocean energy**. CorPower Ocean, a **Swedish** developer of tethered wave energy buoys raised USD 35 million in 2024.
- Around half of the **energy storage and battery** VC was concentrated in the United States while two fast-growing regions, **Canada** and **Korea,** also saw an increase in 2024. Canadian firm VRB Energy raised USD 55 million to develop vanadium redox flow batteries. The largest deal, worth USD 405 million, was secured by a **US**-based iron battery developer Form Energy.
- Fossil fuel-related technologies increased their annual deal value in 2024, with **methane management** attracting USD 430 million in total. Insight M, a US firm developing aerial sensors, raised USD 52 million

While much of the need for energy innovation revolves around hardware, not all start-ups focus on hardware development. In 2024, while over three-quarters of early-stage funding went to hardware developers, the digital energy start-ups saw increased investment. This growth was driven by the influence of AI and the fact that digital companies, with shorter times to market and lower scaling costs, are better suited to high interest rate environments – evident in their lower share of growth equity. In contrast, project developers raised less capital, possibly due to market uncertainty and the lack of bankable intellectual property.

Hardware products often require years of VC funding to meet market needs, but can achieve high valuations and large payoffs for investors. By comparison, energy software and project development companies can scale more quickly but typically offer lower returns. The balance between hardware and software start-ups in early- and growth-stage deals tends to shift with changing risk perceptions.

Share of hardware compared to digital in early- and growth-stage venture capital investment in energy start-ups, 2008-2024

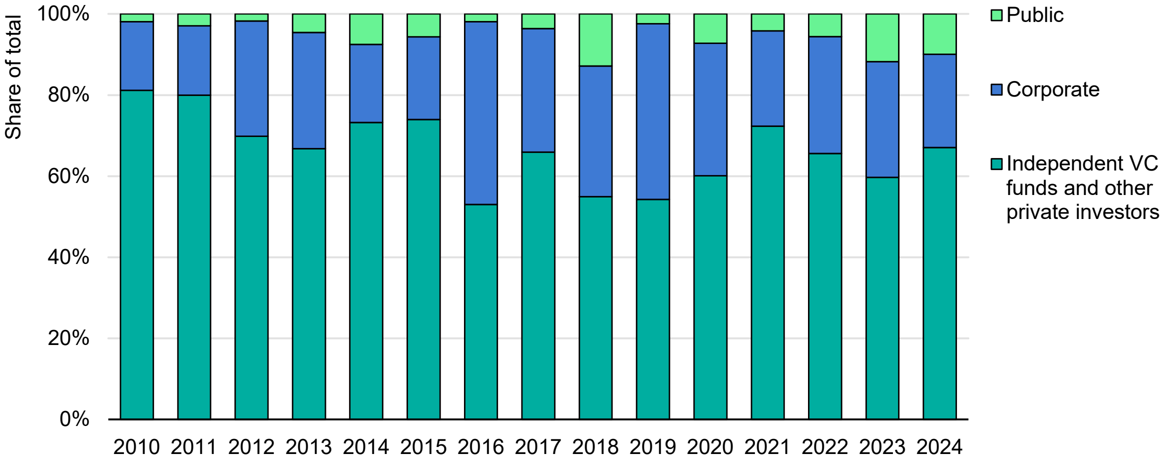


Note: Project development refers to start-ups whose business model involves the development of projects using technologies purchased or licensed from external suppliers.
Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

Sources of investment, with corporate venture capital

Investors in energy-related start-ups can be broadly categorised into those that are primarily financially motivated (such as VC funds, private equity firms and angel investors) and those with wider strategic motivations (such as corporations exploring new technology and opting to acquire it, or the public sector hoping to advance a policy goal). Most VC investment globally comes from non-corporate private investors, accounting for two-thirds of the total in 2024. The share represented by corporate venture capital (CVC) has been relatively constant since 2021, at around one-quarter of the total. Both VC funds and CVC reacted quickly to the current market situation and cut funding in 2023 and 2024. The share of the total from funds that are established or managed by the public sector has risen in recent years and stood at 10% in 2024. The role of governments is generally not to try to “beat the market”, but to offer crucial financial stability to help technologies bridge the valley of death and – as an anchor investor – to attract more private money to deals. In addition, this type of investment can generate a return for taxpayers that can be reinvested in future.

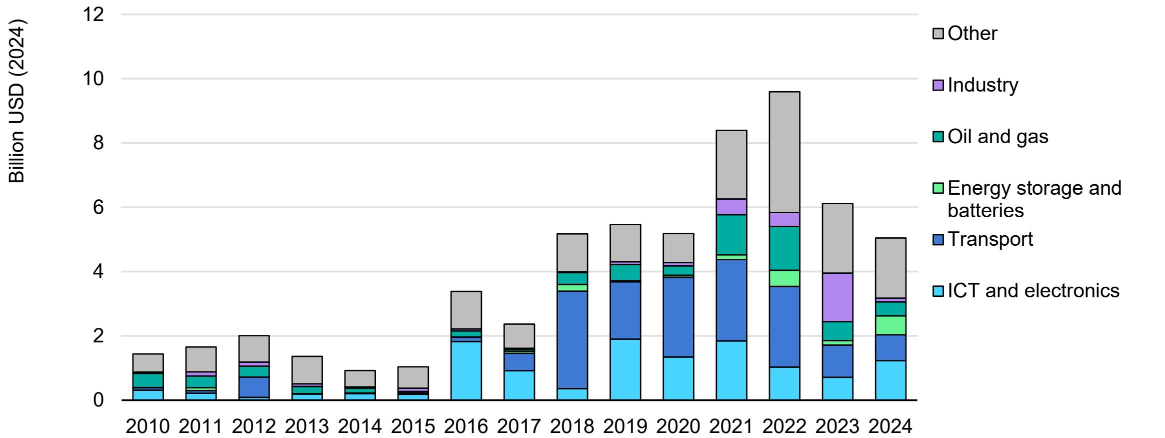
Total early and growth-stage energy-related VC investment, by investor type, 2010-2024



Notes: “VC” = venture capital. Category “Public” includes public-private investors.
Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

Looking more closely at the CVC deals, transport and oil and gas companies cut equity investment in energy start-ups more sharply than other sectors in 2023 and 2024. Firms in heavy industry sectors also invested less, though the effect is somewhat masked by some large deals for steelmaking start-ups in 2023.

Corporate energy-related VC investment, by sector of corporate investor, 2010-2024



Notes: “VC” = venture capital; “ICT” = information and communication technology. “Other” includes categories such as other energy (such as coal and low-emission fuels), buildings (such as appliances, construction and real estate), food and agriculture, forestry, waste and water.
Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

Energy-related CVC from the digital sector trended upwards in 2024, and it is not necessarily directed to energy technologies with an obvious digital connection. Of the 91 deals in which digital CVC investors participated, 18 were for start-ups working on battery technologies, including battery management and optimisation, 15 were focused on energy efficiency, of which 4 were related to heating and cooling, and just 14 were connected to electricity grids, especially grid optimisation. Many more deals went to areas such as CCUS, EVs and the chemical industry, indicating a broader interest in high-tech developments, opportunities to manage the associated data in these sectors and means of compensating for companies' emissions footprints. CVC investments from battery-related corporates were also up in 2024, half of which came from Chinese firms.

Other types of innovation finance

The financial landscape for energy innovation projects is evolving as project developers, investors and governments strive to bring technologies to scale as quickly as possible. Attention is turning to a more diverse suite of financing options, especially for scaling-up and testing technologies at commercial sizes, both in the public and private sectors. For such projects, bringing in debt is important to complement grants, which rarely cover full project costs, and equity, which is usually more expensive. However, affordable debt relies on predictable revenue and guarantees that are difficult to provide for novel technologies. New combinations of financial instruments, sometimes in ways that are familiar to the financial community but not the innovation community, can add value and reduce total scale-up costs for variety of reasons:

- Since 2022, a large amount of liquidity has been withdrawn from capital markets serving innovators, largely due to higher interest rates, inflation and opportunity costs of investing in riskier projects compared with more traditional assets. This has made it harder for energy technology projects to secure funding and scale up smoothly to the next level of development. Some sectors, including hydrogen, have recently found themselves on the downswing of a cycle of investor appetite, as expectations rebalance in light of a continuing gap between higher costs and unrealised market demand. Nonetheless, governments are impatient for new technology ideas to be tested and to inform policy strategy. This convergence of climate policy urgency, inflationary pressures and renewed focus on domestic competitiveness creates a need for capital that can prevent potentially high-impact technologies from stalling due to a lack of operating capital.
- Many governments wish to see multiple large-scale projects that are first-of-a-kind built on their territory this decade, but do not have the resources to support them with sufficient grants. In some cases, projects costing hundreds of millions of dollars can be helped to bridge the valley of death for new technologies, but only by combining multiple public and private financers. This requires new ways

of slicing the project's costs and benefits and allocating them to appropriate sources of finance – "capital stacking" – in ways that maximise the chances of a final investment decision while minimising taxpayer contributions. Strategic investors, including governments and large corporate entities, can help reduce risk perception for other investors and attract debt from a wider variety of sources.

- Some of these large-scale projects are being developed with structures that have significant technological or market risk on two or more sides of a contract (sometime called project-on-project risk). For example, a project to scale-up a technology for hydrogen-based fuels may need to manage risks related to electricity supply for electrolysis, hydrogen supply to fuel synthesis and customer demand for the fuel, with each step controlled by different entities. Creditworthy off-takers who can co-ordinate long-term contracts across the value chain steps are in short supply, requiring stakeholders to co-operate and find public-private solutions for these projects.
- It is increasingly common in the energy sector for new technologies to reach maturity within start-ups. This brings specific funding challenges compared with development in a company with a large balance sheet, because venture-backed start-ups typically only raise capital as equity that can cover a few years of operational expenses. Making the step-up from the laboratory to pilot then large-scale demonstration projects requires a steady flow of ever-larger funding rounds, in which funding delays can bring bankruptcy and project holdups can delay funding. Without a proven track record of project delivery, it can be hard to raise debt or other commercial sources of capital that are cheaper than equity and guarantee a start-up's independence (so-called non-dilutive finance). Given that many energy technology start-ups were founded around 2015, they are now graduating from early-stage funding rounds and looking to scale up risky first-of-a-kind projects that are too large for VC and too risky for traditional project finance. This gap is sometimes called the "missing middle". Governments are exploring ways in which they can help start-ups to maintain short-term working funds that can keep their projects on track (by paying receivables and maintaining inventory in advance of sales). Concessional venture debt is an example of such an instrument. This can help companies stay in their region of origin rather than relocating, and the availability of debt products can also make it easier for start-ups to attract the next round of equity.
- For some start-up companies, a key driver of higher financial costs is their lack of track record and inability to provide performance or loan guarantees. Project-based debt may come with an obligation to set aside collateral worth 100% of the value. Lenders are likely to demand the company's value as collateral as the project itself may not have sufficiently large assets. Governments can help by providing guarantees, though this remains uncommon in most countries, or start-ups can work with large corporate customers who accept some of the credit risk in return for a high stake in the technology.

- For some projects, large corporate promoters struggle to justify the capital costs of technology scale-up projects that compete for capital with more standardised projects in their pipelines. Working with customers, governments, and financial partners to achieve commensurate rates of return with incumbent technology, and keep some of the technology risks off the balance sheet, can facilitate scale-up.
- A lack of a detailed understanding of energy or industrial sector technological principles can severely hinder the ability of financial institutions to engage with a project. Strategic initial investments by experts can help investors distinguish less risky and more impactful proposals, including engagement from philanthropic organisations that have strategic objectives and access to seed capital. Governments can also help to make expertise available to investors, for example from existing demonstration projects, and support matchmaking exercises between innovators and potential financers.

Governments also have an important role to play in ensuring innovators are aware of available financing tools for different stages of technology innovation. Likewise, there is a need to ensure that governments are well-informed of the ways in which these instruments can be used in combination with one another – especially by putting together public and private sources of capital in structured packages – as few of them will be effective in isolation. The EU-Catalyst Partnership, a co-operation between the European Commission, European Investment Bank and Breakthrough Energy (a provider of philanthropic and private capital) is an example of this. Experience with different financing regimes should be shared internationally to support an effective innovation ecosystem globally (see Chapter 6).

Selected financial instruments being used to support energy innovation projects

Instrument	Description	Examples
Venture debt	Venture debt is a loan that does not convert to equity. It can fill the financing gap between equity funding and large-scale project finance, allowing start-ups to scale up while preserving ownership. Some banks offer venture debt to early-stage, high-growth companies that have already raised some capital, for example to scale up from pilot stage to mass manufacturing, or for further R&D on products or services. Its use has grown in recent years.	• The structure of the financial market in the United States has facilitated the availability of venture debt from private sources for some time. The European Investment Bank (EIB) has sought to fill this gap in Europe for energy start-ups. Its product can finance the equivalent of USD 5 million to over USD 54 million at a time, with repayment periods of more than 4 years and interest rates adjusted to the recipient's risk profile. The EIB has signed venture debt contracts worth around USD 2.3 billion with over 100 start-ups in innovation-driven sectors. German company Sunfire, a developer of solid oxide electrolysers, received over USD 100 million in 2024.
Project equity for scale-up	Project finance, or quasi-equity, provides debt or equity to fund infrastructure projects, particularly those with high upfront costs and visible payback periods, including solar and wind farms. It can be a lower-cost form of capital and attractive for borrowers with limited balance sheets, as their other assets are shielded from requisition to cover any repayment debts. However, it is rarely used for innovation projects that carry higher risks than other infrastructure assets, though public entities could develop it to enable such projects.	• In 2024, Breakthrough Energy signed an agreement with US-based Infinium to provide USD 75 million in project equity from its Breakthrough Energy Catalyst platform to Project Roadrunner, which is developing hydrogen-based synthetic fuel.
Loan guarantees	Loan guarantees reduce borrowing risk by involving a third-party institution to underwrite certain risks. They do not require any initial capital from the guarantor, but bear costs related to how much money the guarantor must put aside to insure a portfolio of guarantees.	• In 2024, the United States approved conditional loan guarantees totalling nearly USD 3 billion for two sustainable aviation projects by US-based companies Calumet and GEVO. Calumet finalised its agreement in early 2025.

Instrument	Description	Examples
Convertible debt and grants	Convertible debt, sometimes called a convertible note or convertible bond, is debt (i.e. a loan with an interest rate) that can be converted to a stake in the company (i.e. equity) once certain conditions are met, such as successful project development. When supporting early-stage firms, banks and funds may use convertible debt to manage portfolio risk exposure by increasing their return in cases of success. This can offer more favourable terms than conventional loans, and funders have greater incentives to support day-to-day operations (such as by sharing experience and access to networks). Convertible grants are more likely to be used by the public sector or philanthropies for smaller sums, and do not need to be repaid if fixed criteria are not achieved by the awardee. If the awardee is successful, it is converted to debt and conditions for repayment are triggered.	• Swedish investment firm Baseload Capital secured a USD 24 million convertible loan from Breakthrough Energy Ventures in 2022 for low-temperature geothermal energy. • Oorja, an Indian pay-as-you-go solar irrigation start-up, received a convertible grant equivalent to around USD 300 000 from the DOEN Foundation, which is funded by the Dutch Postcode Lottery.
Advance offtake agreements	A buyer that signs an advance offtake agreement commits to purchase a portion of a project's output before the project is constructed. The agreement demonstrates to potential investors that a project will have a secure revenue stream, reducing financial risk and expanding access to lower-cost capital. The duration of the offtake agreement is crucial, as agreements lasting 10 or more years are typically necessary to attract infrastructure investments and reduce merchant risk. They are often used for projects that involve long lead-times or deployment of innovative technology.	• Swedish company Stegra secured a 7-year offtake agreement with a ventilation firm Lindab in 2024 and will supply 159 000 tonnes of near-zero emissions steel from 2026. The company has other advance offtake agreements with companies including US-based Cargill Metals, German technology manufacturer Zahnradfabrik Friedrichshafen and Finnish heating and cooling technologies supplier Purmo, representing 1.5 Mt of steel per year in total. • In 2024, US-based Fervo Energy secured the world's largest geothermal power purchase agreement to date, a 15-year agreement for 320 MW. • US-based Sublime Systems received commitments worth USD 75 million for low-emissions cement in 2024. • French utilities provider ENGIE and Italian company Energy Dome signed an advance offtake agreement in 2024 for the output of a CO_2 battery, a type of long-duration energy storage technology. • US-based Electric Hydrogen secured a 1 GW framework supply agreement for electrolysers from AES Corporation. • In 2024, US company Ebb Carbon announced an agreement with Microsoft to remove up to 350 000 tonnes of CO_2 over the next decade.

4. Demonstrations, patents and awards

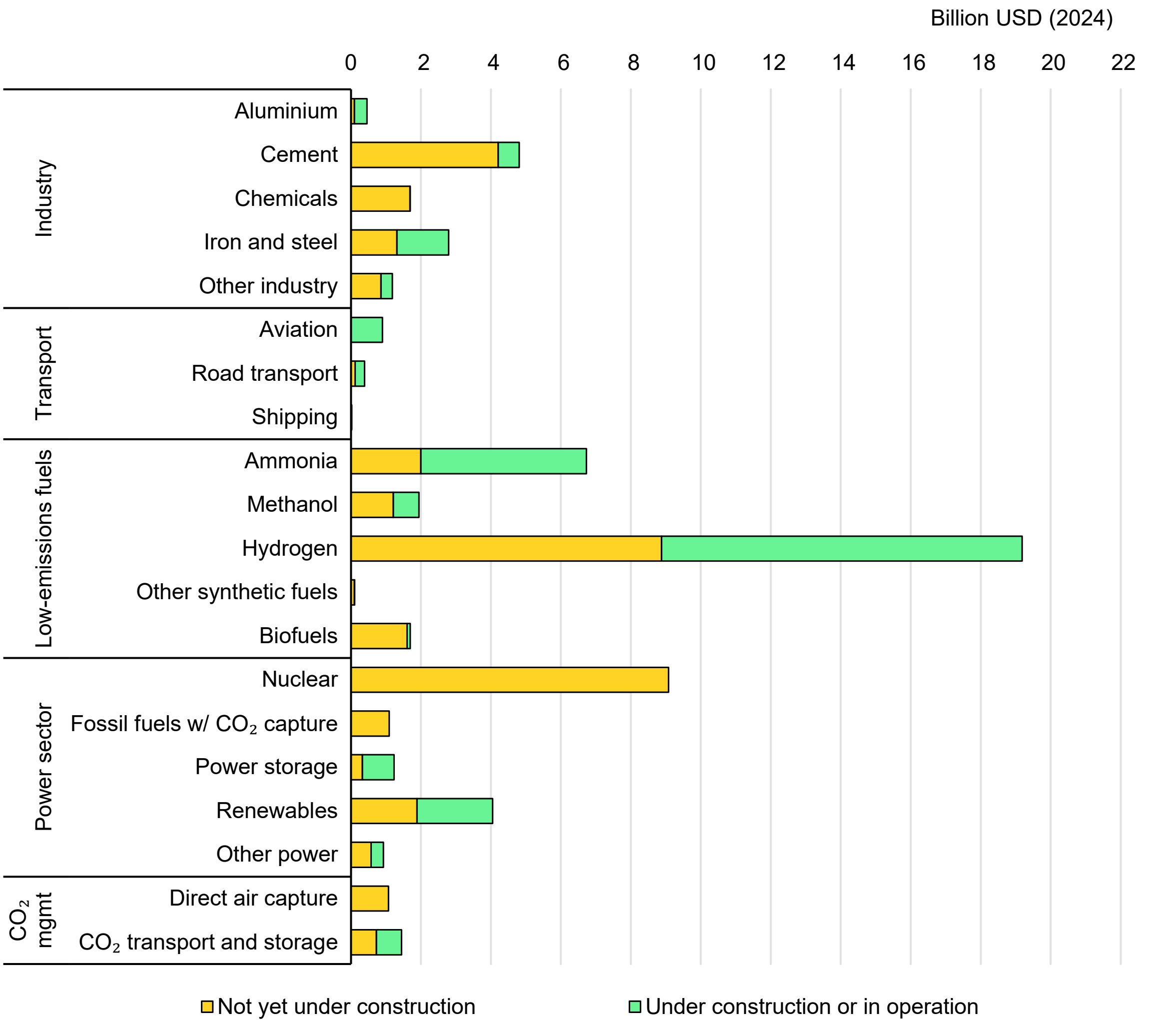
In addition to data on funding, an exploration of further indicators of energy technology developments can provide valuable insights into where innovation efforts are currently being directed. This chapter provides a summary of non-financial trends and indicators of innovation in energy technology, based on information on demonstration projects, patenting data and a selection of recent technology awards. Of course, there are many uncertainties about the role of patents and awards in driving or reflecting innovation, and of the final results of demonstration projects, but they provide a useful perspective on the status of innovation, key topics and market-readiness.

Demonstration projects

For certain energy technologies, constructing and operating large-scale demonstration projects is a crucial step in moving a new concept or design from pilot plant to commercial availability. Such projects are often needed in multiple different technological, geographical, regulatory and market settings in order to build experience and inform regulations and standards. In 2022, 16 governments committed USD 94 billion by 2026 to set up a pipeline of low-emissions energy demonstration projects. Demonstration projects now feature in the policy and strategy documents of major economies, and new funding mechanisms are being developed. Several major projects reached important milestones in the past year (see Chapter 2).

Information from governments and other announcements are tracked in the regularly updated IEA Energy Demonstration Projects Database. It lists around 200 active projects that, if realised, would account for investments of nearly USD 61 billion over the 2022-2035 period, including USD 32 billion of public funds. However, roughly 60% of all funding relates to projects not yet under construction, many of which have pending final investment decisions but are awaiting financial or policy decisions outside their control. The funding is highly skewed towards a small number of very large projects, as fewer than 15 projects (of 200) account for half of the USD 61 billion in total estimated investment. Energy demonstrations are concentrated in North America, Europe, China, and a few other advanced economies in the Asia-Pacific region, such as Australia and Japan. Of the selected active projects over 2022-2035, nearly 60% of the total funding announced or allocated is for projects in North America (primarily in the United States), 25% in Europe and 10% in China.

Total funding for low-emissions energy demonstrations by sector and status, 2022-2035



Notes: "CO_2 mgmt" = CO_2 management. Hydrogen projects with exclusive application in a specific end-use sector (e.g. use of hydrogen in steelmaking) are reported in the corresponding end-use sector, and otherwise under "Hydrogen".
Source: IEA analysis based on the IEA Energy Demonstration Projects Database as of November 2024.

Current trends also indicate much greater emphasis on supply-side rather than demand-side technology. If the active demonstration projects listed in the database proceed as planned, funding would be concentrated in two supply-side sectors, namely hydrogen and hydrogen-based fuels, and nuclear power generation. Around half of the total funding was for projects focusing on hydrogen and hydrogen-based fuels production, and another quarter on power generation, such as for advanced nuclear designs and floating offshore wind. These trends suggest that there are still many untapped funding opportunities on the demand side, in sectors such as aluminium, aviation and shipping. Heavy industry, where projects for low-emissions cement and steel account for a significant share of all projects, is an exception.

The costs of demonstration projects vary across sectors. For nuclear fission, the average expected capital expenditure is around USD 3 billion per project. For hydrogen production, it stands at around USD 0.5 billion per project. For heavy industry, projects are projected to cost over USD 200 million on average. Projects in other end-use sectors, such as electricity storage or road transport, tend to be smaller, costing less than USD 50 million. Given the high costs, it is important for stakeholders to consider how international collaboration can enable knowledge-sharing to help subsequent projects build on prior experience.

What is an energy technology demonstration project?

A commercial demonstration project is a large-scale example of a process that still carries technological risk, i.e. that has not yet been operated long enough at scale to guarantee the performance of future installations. Demonstration projects provide evidence of technical feasibility and commercial-scale operations, as well as providing a regulatory stress-test and building social licence. They reduce the perception of risk for financiers and insurers, thereby facilitating investment in subsequent installations, for example from infrastructure funds or project finance banks. While a demonstration project does not have to be the first of its specific design, it does need to be the first that demonstrates its goals in a relevant environment (a new regulatory regime or geographical region, for example). If several projects meeting these criteria are simultaneously under development, they may all be considered as potential first-of-a-kind facilities.

In the IEA's ETP Energy Technology Guide, technology readiness level (TRL) 8 or "first-of-a-kind commercial" is applied to technologies that demonstrate successful operation of a new design over several years, at the scale of a full commercial unit, utilising a given technology within a given sector, or in a new type of market and regulatory environment. Initial operation of the technology at scale, but without enough experience to optimise the operations or evidence market and regulatory aspects, means that a demonstration project is listed as TRL 7. It is important to distinguish this step from field trials and other initiatives aiming to pilot the deployment of a technology that has already been demonstrated. Governments in different countries might use different criteria to categorise demonstration projects, but the common definition used in the Energy Technology Guide is inclusive of the core elements noted above, and allows cross-country analysis.

Such first-of-a-kind (and often second-, third-, fourth- or fifth-of-a-kind) projects can be hard to finance, given the significant risk and capital required to learn about the effectiveness, affordability and market-fit of certain technologies at commercial scale. In sectors such as heavy industry, thermal power generation and fuel transformation, a demonstration project can run to several billion dollars and require many years of planning followed by several years of operating at a loss in order to accumulate sufficient experience. For these technologies, which have large unit sizes and are not mass-manufactured, the “valley of death” moniker given to the period between TRL 6 and TRL 8 is particularly apt – technologies do not make it to the other side without committed financial support from the public and private sectors.

Patenting

Patents, as a formalised measure of intellectual property, provide an indicator of where innovation is taking place. They serve as early indicators of technological developments that have the potential to drive energy transitions and stimulate economic growth.[7] The analysis of patent data can also help reveal whether innovators are responding to policy signals: an increase in patents related to renewable energy technologies, for example, can indicate alignment with policies promoting such technologies. This kind of responsiveness from innovators is crucial for achieving long-term strategic goals for accelerating clean and affordable energy transitions. Patent data can also uncover the geographical distribution of innovation, thereby providing valuable information for policy makers, investors and researchers on competitive advantages and collaboration potential. The IEA collaborates with the European Patent Office (EPO) to track patent trends in the energy sector, providing a global, comprehensive and up-to-date analysis of patent families and related themes. Recent joint efforts between the IEA and EPO have explored patenting for hydrogen and electricity grids, and these technology areas are highlighted in this section in addition to the general energy-related trends.

Trends in energy technology patenting

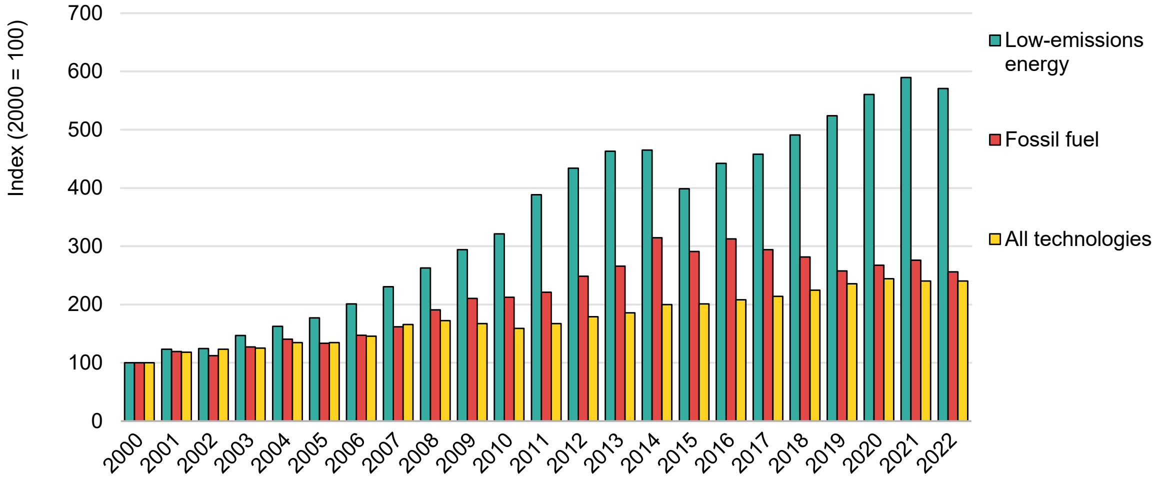
According to data made available in March 2025, the number of patents for low-emissions energy technologies declined in 2022 for the first time since 2015. Previously, the published international patent families (IPFs) for low-emissions energy technologies had been increasing at a faster rate than the global average for all inventions.[8] One explanation is that the slowdown in 2022 is an artefact of fewer applications 18 months before during the Covid-19 pandemic. If so, it may

[7] However, it is also well known that while patents reflect innovation efforts, they do not always encourage uptake of the invention. The recent rise of lithium iron phosphate (LFP) batteries for electric vehicles occurred only after patents expired in 2017-2022 for which applications had been made from 1997, but were not successfully converted to market-leading products.
[8] IPFs each represent a unique invention and include patent applications targeting at least two countries. They are used in to represent inventions of sufficient quality and commercial promise that the inventor wishes to protect them in multiple jurisdictions. For detail on categories used in this section, see the EPO and IEA report Patents and the Energy Transition (2021).

not be a true reflection of less innovation and may be "corrected" if a higher rate of patent publishing is observed for 2023 when data is published in 2026.

Energy technology patents can be categorised into fossil fuel patents and low-emissions energy patents, which provides a lens on the role of innovation in ongoing energy transitions. Between 2000 and 2022, the number of low-emissions energy IPFs was over four-and-a-half times the number of fossil fuel IPFs. For supply-side energy technologies in isolation, low-emissions patenting overtook fossil energy patenting in the early 2000s. Fossil fuel patenting peaked in 2014 and since 2019 has stabilised at a lower level.

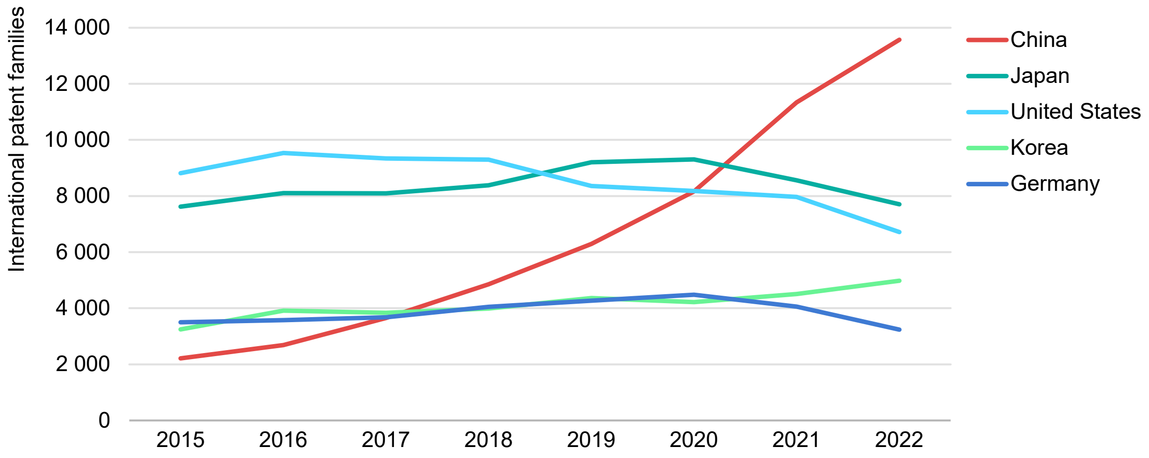
Global evolution of patenting in low-emissions energy versus fossil fuel and other technologies, 2000-2022



Note: Shows a count of international patent families, each of which represents a unique invention and includes patent applications targeting at least two countries.
Sources: IEA analysis based on data from the European Patent Office (EPO), and EPO and IEA (2021), Patents and the Energy Transition.

China's share of energy patenting has increased markedly since 2016, when it filed fewer IPFs than each of the United States, Japan, Germany and Korea. Its share has risen from 7% in 2015 to 30% in 2022, and in 2022 it filed 76% more IPFs than the next highest, Japan, which overtook the previous leader, the United States, in 2019. Unlike the United States, where one-quarter of the energy patenting is in fossil fuel areas, most of China's energy patenting is in low-emissions energy (96% in 2022), and its low-emissions energy patenting has risen at over twice the rate of its fossil fuel patenting since 2015. In the period 2015-2022, Japan's ratio of low-emissions energy patenting to fossil fuel patenting was even higher than China's. Today, most countries have more patents in low-emissions energy technologies than in the fossil fuel category. Saudi Arabia is an exception, however: it recorded almost four times more patents related to fossil fuels than to low-emissions energy between 2015 and 2022.

Energy patenting of the five countries with the most applications, 2015-2022

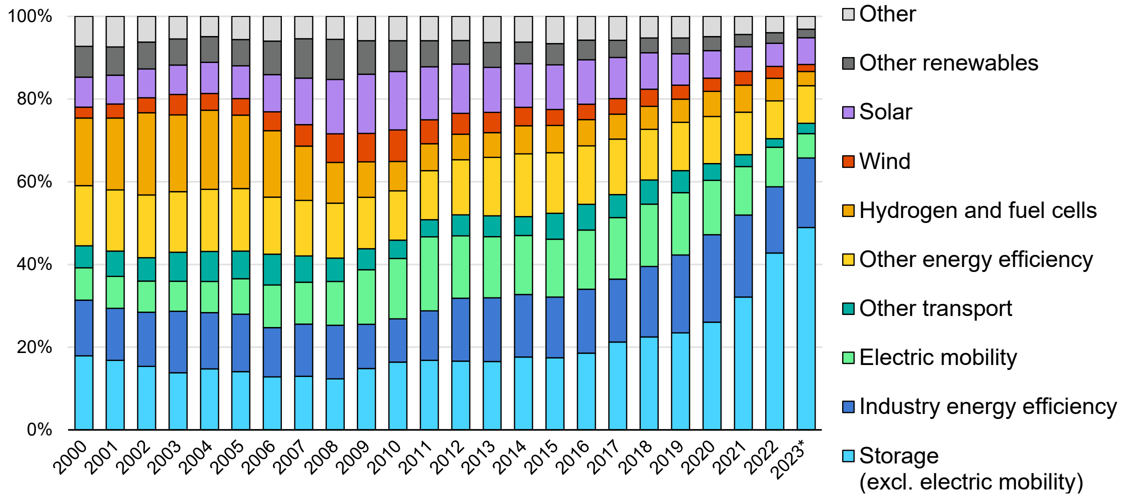


Note: Each international patent family represents a unique invention and includes patent applications targeting at least two countries.
Source: IEA analysis based on data from the European Patent Office (EPO).

Among different categories of low-emissions energy technology patents, energy storage (excluding electric mobility applications) has emerged as the most significant, representing around a third of all low-emissions energy patents granted between 2020 and 2022. Notable activity has also been observed in several other categories, including industrial energy efficiency, accounting for over 19% of patents filed in the past 3 years, and electric mobility, reaching almost 12% after some fluctuations. Regional differences in patent distribution are evident. In China, 18% of patents between 2020 and 2022 focused on energy storage, while 17% were related to solar technologies. In India, a significant 39% of patents were directed towards industrial energy efficiency. Meanwhile, in Germany, 25% of patents targeted storage, and 23% were aimed at electric mobility between 2020 and 2022. Initial data on patent applications for 2023 indicate that storage continues to dominate and increase its global share of the total.

Today, more innovation effort goes towards small-scale and modular energy technologies such as batteries and electrolysers, but there are important international differences: around half of China's energy patenting and 90% of its venture capital is directed to mass-manufactured low-emissions technologies, and innovation in these areas has helped underpin China's lead in several energy technology supply chains. Likewise, around 50% of Europe's energy patenting is for smaller-scale low-emissions technologies, but it is also active in large engineering projects that generally have more uncertain impacts on long-term competitiveness. By comparison, the United States has a more balanced portfolio of inventions across fossil fuel as well as large- and smaller-scale low-emissions technologies, with its large venture capital market having the capacity to place bets on all of them.

Low-emissions energy patents by technology, 2000-2023



* The datapoints for 2023 are considered provisional due to the time lag in filing applications in the PATSTAT database.
Notes: Category "Other" includes patents in nuclear; vehicle fuel efficiency; carbon capture, utilisation and storage; and grid technologies. Based on international patent families, each of which represents a unique invention and includes patent applications targeting at least two countries.
Source: IEA analysis based on data from the European Patent Office (EPO).

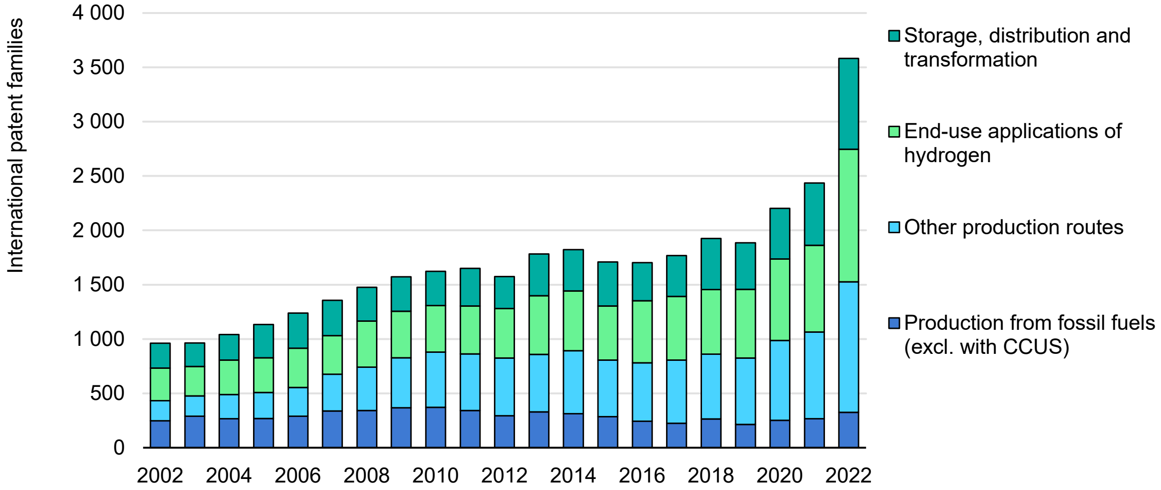
Hydrogen-related technology patenting is rising again

Global patent applications related to hydrogen jumped by 47% in 2022, with most of the growth coming from the patenting of technologies that are primarily motivated by the integration of hydrogen in a low-emissions energy system.[9] Patents in electrolysis; carbon capture, utilisation and storage (CCUS); and other production routes for low-emissions hydrogen have increased steadily over the past 20 years, while patents targeting fossil fuel-based production technologies that do not mention CCUS have largely stagnated, though there was a small uptick in 2022.

Most hydrogen-related patents centre on production and end-use technologies, whereas growth in patents for storage, transport and transformation technologies has been slower. IPFs for electrolysis have trebled over the past decade, boosting patenting activity in hydrogen production technologies. More than 90% of IPFs for hydrogen end-use applications are classed as being motivated by climate, targeting uses in transport, iron and steel manufacturing, buildings and electricity generation. Patents related to the automotive sector continued to grow strongly in 2022 and represented almost two-fifths of patenting activity in end-use applications. Ammonia production also stood out in 2022.

[9] The scope of technologies considered to be hydrogen-related is broader than the "hydrogen and fuel cells" category used elsewhere in this section. It cuts across other categories including CCUS and end-uses of hydrogen such as those in industry.

Worldwide patents in energy-related hydrogen technologies, 2002-2022



Notes: "Excl. with CCUS" means that patents for the application of carbon capture, utilisation and storage to hydrogen production methods are included in "Other production routes". Each international patent family represents a unique invention and includes patent applications targeting at least two countries.

Sources: IEA analysis based on data from the European Patent Office (EPO), and EPO and IEA (2023), Hydrogen Patents for a Clean Energy Future.

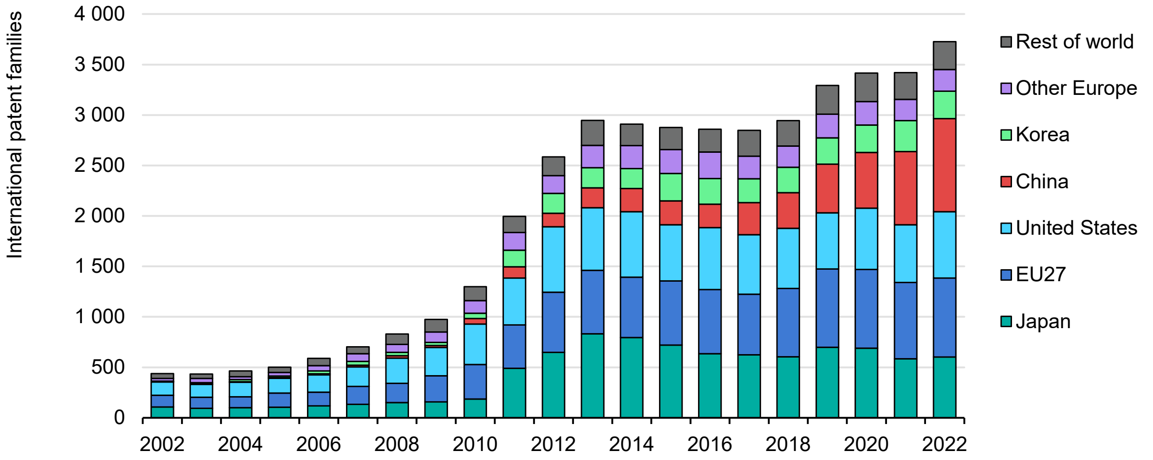
The European Union leads patent applications related to hydrogen, followed by Japan and the United States. In 2022, applications in the European Union increased by around 55%, growing at a much faster rate than in Japan, which had a similar number of patent applications in 2021. There were also notable increases in the United States (34% year-on-year growth), Korea (40% growth) and China (18% growth). While the European Union and Japan have long sustained steady growth in hydrogen patenting prior to 2022, the United States experienced its first significant uptick for some time, despite having led hydrogen IPFs before 2011.

Patenting for electricity grids continues to grow

Patenting activity related to electricity grids[10] experienced a marked acceleration between 2009 and 2013 and a modest increase since 2018. This is an encouraging trend given that modern, smart and expanded electricity grids are important for secure energy transitions but are sometimes overlooked, especially in terms of the technology innovation needs. The early growth was driven primarily by developments in Japan, the European Union and the United States. While growth has since stabilised in these regions, China has entered a rapid expansion phase, and now accounts for 25% of patents in electricity grid technologies, playing a pivotal role in driving the overall increase in grid-related IPFs since 2018.

[10] The scope includes technical improvements to traditional grid components, newer types of hardware for adapting the grid to the demands of a low-emissions energy system and the diverse range of digital tools (both hardware and software) to enable responsive communication and control.

Worldwide patents in electricity grid technologies, 2002-2022



Note: Each international patent family represents a unique invention and includes patent applications targeting at least two countries.
Sources: IEA analysis based on data from the European Patent Office (EPO), and EPO and IEA (2024), Patents for Enhanced Electricity Grids.

Smart grid innovations are driving the recent growth in grid patenting activity. These technologies aim to optimise energy efficiency, integrate renewables and enhance reliability by using digital technologies, automation and two-way communication. Between 2011 and 2022, Japanese applicants led innovation in smart grid applications, accounting for about one-fourth of all IPFs during this period, with a focus on demand response and virtual power plant technologies. A substantial number of smart grid patents also originated from the United States, particularly in smart metering and market operations, followed by the European Union.

An area worth highlighting is grid-related artificial intelligence (AI) patenting, which has grown approximately 34% on average annually since 2016. The main technologies targeted by AI-related IPFs are those supporting forecast- and decision-making, which account for 39% of the AI-related IPFs. AI for innovation in smart grids is now the most active area of patenting among enabling digital technologies, and is led by the United States and China, with 24% and 23% of AI-related patents, respectively.

Also notable are patents related to smart electric vehicle (EV) charging, which experienced a more than sevenfold increase in patenting activity from 2008 to 2013. Following a short decline, patenting activity in this area returned to growth in 2017, achieving an average annual increase of 17%. Despite China's leadership in EV deployment and manufacturing, its contribution to smart EV charging patents remains modest, with Japan, the European Union and the United States driving activity.

Patenting activity for physical grid technologies has been similarly robust, with a noticeable upswing since 2009. European applicants lead this field, holding 39% of IPFs in power generation integration, 29% in grid storage technologies, and 25% in power conditioning. These advances are vital for grid stability and renewable energy integration. For example, to address the stabilisation challenges of grids with high renewable energy penetration, patenting in non-spinning inertia technologies has increased since 2018. Key technologies include synthetic inertia alongside large-scale battery storage systems and flywheels. Another technology, superconducting cables, could almost eliminate electricity transmission losses and reduce curtailment, among other benefits. Patenting activity in this domain experienced an uptick in 2018, with applications related to cable designs and to methods for using superconductivity in electricity transmission, but growth has since slowed. It is not yet clear whether this reflects lower enthusiasm for near-term market opportunities or slowing technical improvements towards technology maturity.

Energy technology awards

Technology awards for successful projects, collaborations or individuals can serve to showcase technology progress and advances, and therefore provide another window into innovation in energy technology. The IEA Technology Collaboration Programmes (TCPs) and Mission Innovation, among other organisations, organise annual awards in different sectors to recognise innovation progress and project advances. While some of these awards have been distributed periodically for more than 20 years, including the Solar Heating and Cooling Programme Solar awards, others, such as the Hydrogen TCP Awards of Excellence, were introduced more recently. In 2024, Mission Innovation launched a series of awards for innovation in energy-intensive industries. The 2024 winners of these awards are summarised in this section in recognition of excellence and to highlight the areas of progress that experts within the IEA community consider especially promising.

Awards for technology excellence from IEA Technology Collaboration Programmes and from Mission Innovation in 2024

Award and criteria	2024 winner	Country	Key achievements
Hydrogen TCP Awards of Excellence 2024 For innovation in hydrogen technology and applications, international research, collaboration, development and practical implementation.	SWITCH (Smart ways for in-situ totally integrated and continuous multi-source generation of hydrogen) Consortium.	The Netherlands, Germany, Switzerland, Poland, and Italy	• **Successful operation** in 2024 of a flexible, modular and reversible 70 kW (electrical input) **solid oxide module prototype** to produce hydrogen, heat and electricity. • A durability **test over 1 000 hours** showed the safety of switching between electrolysis and fuel cell modes during operation.
	Science Center of Shanghai Jiaotong University and Shanghai Hyfun Energy Technology for solid hydrogen storage and transportation technology.	China	• Creation of a magnesium-based device that **stores 3-4 times more** hydrogen with **nearly one-third of the costs** of a 20 MPa tube trailer.
International Smart Grid Action Network (ISGAN) Award of Excellence 2024 For leadership and innovation in smart grids projects.	Korea Power Exchange for inertia analysis, energy storage systems optimisation and demand response advancements.	Korea	• Commissioning of a **research study on a real-time inertia** monitoring system evaluating the minimum system inertia.
Solar Heating and Cooling Programme (SHC) Solar Award 2024 For solar thermal technologies in industrial processes reducing costs and emissions.	LACTOSOL project, led by Newheat, at Lactalis site in France.	France	• The **second-largest solar thermal plant supplying an industrial** site in Europe. • 15 000 m^2 solar thermal collectors and approximately 8 000 MWh of energy annually used to dry liquid whey powder for dairy products, reducing the site's gas consumption by 6%.
Solar Power and Chemical Energy Systems (SolarPACES) Award for Technology Innovation and Lifetime Achievement Award	Dubai Electricity and Water Authority for its 950 MW CSP Hybrid Power Plant Phase IV.	United Arab Emirates	• The world's largest and most efficient hybrid solar project with the largest solar tower and thermal energy storage capacity. • Combines **250 MW of PV, 600 MW trough and 100 MW tower CSP**. • Record-low levelised cost of electricity at USD 0.073/kWh.

Award and criteria	2024 winner	Country	Key achievements
For innovations improving concentrated solar power (CSP) technology and personal contributions to the development and implementation of CSP systems.	Aldo Steinfeld (ETH Zürich) and Manuel Romero (IMDEA Energía).	Switzerland and Spain	• Over 20 years pioneering and developing **concentrated solar power technology to produce synthetic fuels**, including the first solar tower demonstration of kerosene from water and CO_2.
Mission Innovation Net-Zero Industries mission Net-Zero Industries Award For young talents, female innovators, outstanding projects and international advancement in the global south.	Young Talents: Cameron Halliday (Mantel)	United States	• **Successful development of molten salt-based carbon capture** technology operating at high temperatures and foundation of a start-up to commercialise this technology: Mantel aims to bring the technology from lab to industrial scale and has announced a nearly USD 17 million project in the paper and pulp industry.
	Female Innovators: Karen Scrivener (Ecole Polytechnique Fédérale de Lausanne).	Switzerland	• Pioneering work in **concrete and cement** materials over 40 years.
	Outstanding Projects: Calix ZESTY – Zero Emissions Steel Technology	Australia	• Proof of effectiveness of **hydrogen direct reduced iron** (H_2-DRI) technology for iron and steel industry. • Financing a 30 000 tonne per year **demonstration plant which is in construction.**
	International advancement in the global south: Cemex project "Harnessing Solar Radiation to Drive CO_2-free Clinker Manufacturing", in collaboration with Synhelion.	Mexico	• Pilot-scale **production of clinker using high-temperature solar radiation** in 2022 and continuous clinker production over extended period achieved in 2023.

5. Races to firsts

The information and analysis presented in this report provides a snapshot of the state of energy innovation. From the various highlights, metrics and updates emerges a picture of intrepid effort and progress, mixed with various valiant struggles to take the next steps up to larger scales. These struggles are characterised by complexity – of projects, value chains, industrial priorities and market signals. They are most notably evident for large-scale first-of-a-kind projects that must overcome a range of non-technical challenges related to finance, business models, public support, safety standards, connection to energy infrastructure, tariff design and offtake contracts.

If these surmountable challenges are overcome, the benefits will be large. In a scenario based on the policy settings in 2024, the global market for EV batteries is set to reach USD 145 billion by 2035, while that of solar PV modules and heat pumps combined is set to reach USD 171 billion. Worldwide, the market size for near-zero emissions materials, such as steel and cement, is set to reach USD 26 billion by 2035.

To celebrate, track, encourage and communicate progress towards a selection of the outstanding scale-up challenges we have defined 18 "races" that are described in this chapter. These are key milestones that we believe are achievable by around 2030 with sustained policy support and towards which we know of innovators working hard stay on track (see Chapters 2 and 6). They do not derive from any modelling of scenarios, but are bottlenecks through which the technologies will have to pass if they are to help bring more secure or low-emissions energy to all corners of the global economy. Most relate to demonstration of solutions at scale – the sooner they are achieved, the sooner they will be able to be deployed and have real-world impact. They cut across three main themes: long-term energy security, environmental protection, and technology areas with significant potential to generate scientific spillovers to the broader economy.

For each race, several projects and companies are currently vying to achieve the milestone first, mostly before 2030 and often with competing technology options. Wherever possible, the races are therefore defined to be technology neutral. Their criteria are as precise as possible to allow their achievement to be clearly identified. Progress towards the finish line represents much more than technical development; it shows that innovators are also navigating the non-technical obstacles that stand in their way, and which deserve equal recognition and support from policy makers and other actors.

In the following pages, we provide a global snapshot of where each race stands today. The IEA will provide updates on progress from the frontrunners as a means of recognising excellence and identifying areas for further support and action. Not all races will conclude on the same timeline – some milestones may be realised as early as 2026 while others will not be achieved until 2030 at the earliest. Over time, new races may be added to represent other key innovation priorities.[11]

When a race has clearly been won, the IEA will widely communicate each success and disseminate insights into how it was achieved. In many cases it will be appropriate to also herald the runners-up as they prove their technologies in different contexts. We look forward to celebrating each step of progress along the way, and recognising the public and private teams that help deliver step-changes in the available energy technology portfolio. We hope that the first races will inspire the international community to get behind the pioneers for each one.

[11] In seeking to tightly define these races, we have found it infeasible to include some important technology areas for which clear criteria are lacking or data for tracking progress is unavailable. These include district heating and cooling, grid-enhancing technologies, micro and mini grids, virtual power plants, building energy efficiency, and data centre performance, among others.

Races to firsts

Phases:

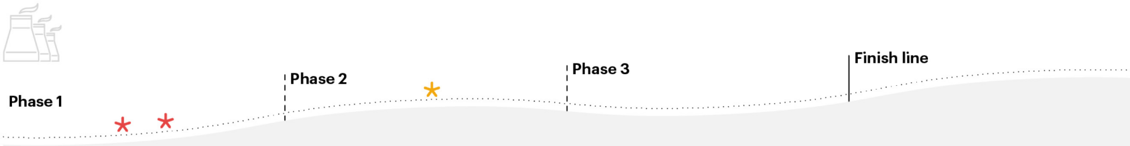
- Phase 1 — Testing at smaller scale or in different configuration
- Phase 2 — Raising funds and preparing
- Phase 3 — In construction and could meet criteria
- Finish line — Meets criteria

Technology readiness levels (TRL) of the updates refer to the highest level achieved for the technology design in question by the named company or consortium.

Long-term energy security

First repeatedly-deployed **nuclear small modular reactor** or micro reactor

Successful commissioning of three or more installations at different sites of the same nuclear reactor design, including in two different countries.



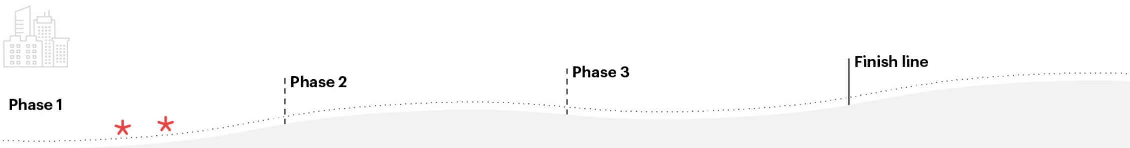
- (Phase 1) 2024: The internal reactor components at the Linglong One 385 MW thermal plant were put in place in China, aiming for operation in 2026, at a scale larger than 250 MW thermal.
- (Phase 1) 2024: Early-stage site preparation works were completed by Ontario Power Generation for a planned 4x300 MW_e project in Canada using US-based GE Hitachi's BWRX-300 design.
- (Phase 2) 2023: The HTR-PM demonstration reactor started commercial operation at 250 MW thermal in China (TRL 8).

Criteria. Scale: 300 MW_e or less; **Other:** Can be for terrestrial electricity or heat supply purposes.

Emissions reduction

The first **solid-state cooled building**

Use of solid refrigerant technologies as the main means of air conditioning.



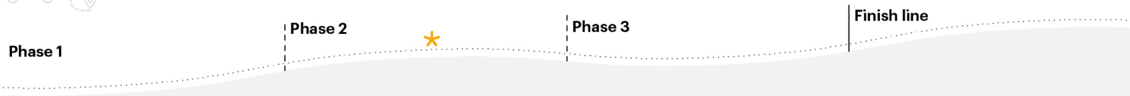
- (Phase 1) 2024: UK start-up Barocal unveiled a prototype in the United Kingdom that matched the thermal performance of vapour compression systems in small-scale applications (TRL 5).
- (Phase 1) 2024: Hong Kong University of Science and Technology announced an elastocaloric cooling cascade system with 48% higher efficiency than previous versions (TRL 5).

Criteria. Scale: Multioccupancy residential or tertiary building. **Period**: Each day over a period of one summer month.

Technological spillover potential

The first electric **vehicle with a solid-state battery**

Serial production of a vehicle on the market powered entirely by a fully solid-state battery.



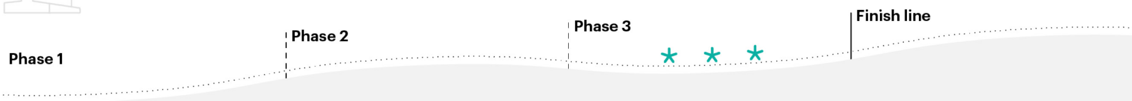
- 2024: Korean manufacturer Samsung SDI announced it has tested a cell in Korea with 500 Wh/kg that can charge in 9 minutes and last 20 years. It plans to be selling fully-solid-state batteries by 2027 (TRL 6).

Criteria. Scale: 10 000 or more at least 4-seater vehicles or equivalent. **Period:** Cumulative over 12 consecutive months.

Emissions reduction

The first large-scale plant producing **iron-based near-zero emissions steel**

Crude steel produced primarily from iron with 400 kilogrammes CO_2-equivalent per tonne or less.



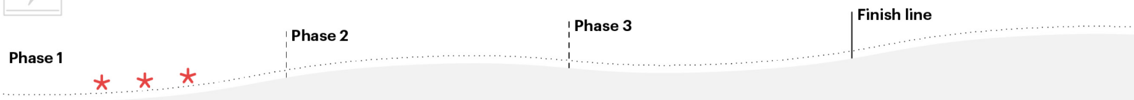
- 2024: Swedish start-up Stegra reached financial close on the Boden plant in Sweden, aiming for operation at a scale of 2.5 million tonnes in 2026.
- 2023: Construction started at the Hebei Bishi steel plant in Inner Mongolia, aiming to be online in 2025 at a scale of 2 million tonnes.
- 2023: Norwegian start-up Blastr Green Steel reached the Environmental Impact Assessment stage for a 2.5 million tonne plant in Finland.

Criteria. Scale: 1 million tonnes of steel. **Period**: Cumulative over 12 consecutive months. **Other**: Crude steel produced primarily from iron (<30% scrap) with 400 kg CO_2-eq per tonne or less. Direct and substantive indirect emissions included.

Long-term energy security

First large-scale **long-duration storage battery**

Multiple cycles of a system that stores electrical energy from a power grid at a single site in electrochemical form and returns it to a customer via the power grid at least one week later.



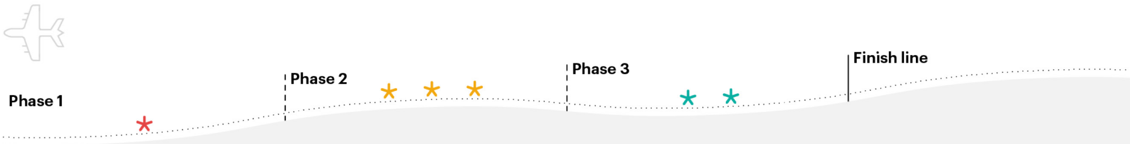
- 2024: Rongke Power, a Chinese manufacturer of vanadium flow batteries, commissioned a 700 MWh (minimum 4-hour discharge time) system in Xinjiang (TRL 8) and is constructing a similar 800 MWh facility in Dalian.
- 2024: Form Energy, a US start-up, started construction of a 150 MWh (minimum 100-hour discharge time) iron air battery and is planning one at 500 MWh (TRL 7).
- 2023: ESS, a US technology developer, partnered with LEAG, a German energy provider, to start building a 500 MWh (minimum 10-hour discharge time) iron flow battery (TRL 7).

Criteria. Scale: 1 GWh electrical energy storage capacity. **Period:** During a period of less than 1 year. **Other:** Cycles involving at least 25% of the storage capacity.

Long-term energy security

First refinery-scale next-generation **sustainable aviation fuel** plant

Sale of aviation fuel whose energy content derives entirely from electricity, lignocellulosic biomass, and/or algae to airline operators or their fuel suppliers.



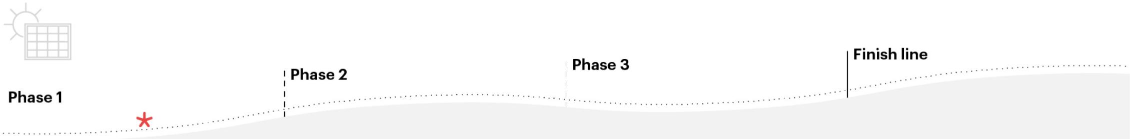
- ★ 2024: A H_2-based fuel plant entered operation in Germany at around 350 tonnes per year in Germany (TRL 6).
- ★ 2024: Infinium, a US start-up, announced offtake agreements and project equity for a H_2-based fuel plant of around 25 000 tonnes, which they plan to build for operation by 2026.
- ★ 2023: US-headquartered HIF Global initiated engineering studies for a H_2-based fuel plant in the United States with a capacity of around 500 000 tonnes per year, aiming for operation by 2030 (TRL 6).
- ★ 2023: A consortium including DHL announced a 200 000 tonne per year hydrogen-based fuel project plan for 2030 in Germany (TRL 6).
- ★ 2025: A 2 500 tonnes H_2-based fuel plant entered construction in Germany.
- ★ 2024: Chinese company Shanxi International Energy Group reportedly signed an agreement with a local government in northern China to build a H_2-based fuel plant for 350 000 tonnes per year, starting initially with 100 000 tonnes per year of capacity.

Criteria. Scale: 100 000 tonnes of kerosene equivalent. **Period**: Cumulative over a period of 12 consecutive months. **Other**: Fuel must be of a type that is blendable with JP-8 or Jet A-1 fuel at levels of at least 50%. Any carbon inputs are sourced from lignocellulosic biomass, algae, fermentation, biomass digestion or CO_2 captured from the atmosphere or ocean via direct air capture.

Technological spillover potential

The first commercial **30% efficient solar** photovoltaics

Production of a solar module design with a nameplate conversion efficiency of 30% or more.



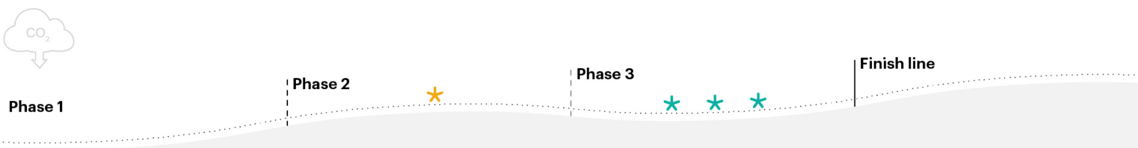
- ★ 2024: UK company Oxford PV sold the first output from their megawatt-scale pilot manufacturing line for 24.5% efficient modules in Germany (TRL 4).

Criteria. Scale: 100 MW or more. **Period:** Cumulative over 12 consecutive months.

Long-term energy security

First large-scale **multi-source CO_2 storage hub** in operation

A single CO_2 storage site stores CO_2 from at least three different sources.



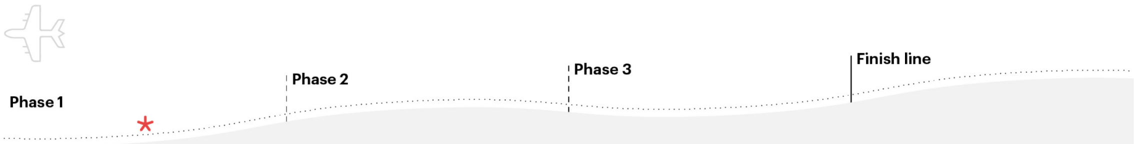
- ★ 2022: Canadian company Enhance Energy announced preparation of the Origins project that they plan to be available to store CO_2 from 2025, and could connect to two existing CO_2 capture facilities supplying the company's enhanced oil recovery activities.
- ★ 2024: US-based ExxonMobil is developing several storage sites and in 2024 signed agreements with six potential CO_2 sources totalling 6.7 Mt per year.
- ★ 2023: the Porthos storage site in the Netherlands entered construction for operation by 2026 for the first of four CO_2 sources (500 000 tonnes).
- ★ 2024: The Northern Lights storage site completed construction in Norway and has at least four CO_2 sources lined up to supply CO_2 from 2025 (400 000 tonnes), 2026 (430 000 tonnes), 2026 (800 000 tonnes) and 2029 (350 000 tonnes).

Criteria. Scale: Each of the three sources contributes 100 000 tonnes of CO_2 or more. **Period:** Cumulative over 12 consecutive months. **Other:** Must be verifiable according to a dedicated regulatory regime.

Technological spillover potential

First **carbon-free flight**

A safe continuous flight of 1 000 km or more with no propulsion from a carbon-containing fuel.



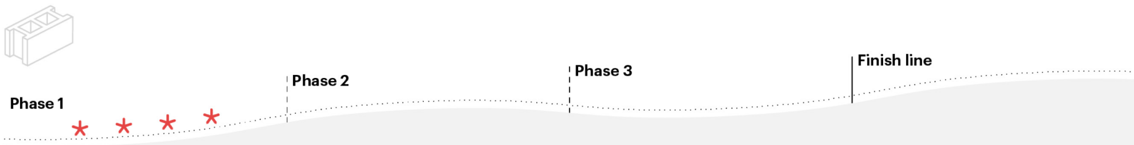
* 2024: US company Joby Aviation completed a manned 840 km test flight of a hydrogen-powered 4-passenger plane in the United States (TRL 6).

Criteria. Scale: Aircraft capable of carrying 20 passengers or equivalent.

Emissions reduction

The first large-scale **near-zero emissions cement** plant

Cement produced with 40 to 125 kg CO_2-eq per tonne and sold or otherwise transferred for commercial use in load-bearing applications.



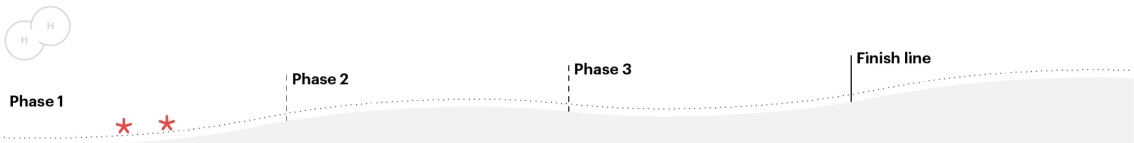
* 2025: EcoCem, and Irish company, took an investment decision to build a 300 000 tonne per year facility in France for low-clinker, high-filler cement, targeting operation by 2026. While this plant will not fully meet the emissions criteria, it takes the company a step closer (TRL 7).
* 2024: Brimstone, a US start-up, was awarded a government grant to help build a 140 000 tonne plant using its silicate-based technology, and is now pursuing a final investment decision (FID) (TRL 4).
* 2024: UK start-up Cambridge Electric Cement raised money for larger pilot-scale tests of its electric arc furnace approach (TRL 3).
* 2024: Sublime Systems, a US start-up, was awarded a government grant to help build a 140 000 tonne plant using its electrolytic process, and is now pursuing FID (TRL 4).

Criteria. Scale: 750 000 tonnes or more. **Period:** Cumulative over 12 consecutive months. **Other:** Emissions threshold rises linearly from 40 kg CO_2-eq per tonne for 0% clinker to 125 kg CO_2-eq per tonne for 100% clinker. Direct and substantive indirect emissions included. Any CO_2 storage must be verifiable according to a dedicated regulatory regime.

Long-term energy security

First fast-cycling **underground hydrogen storage** facility

More than three injection and withdrawal cycles achieved within a year, and the withdrawn hydrogen transferred for use.



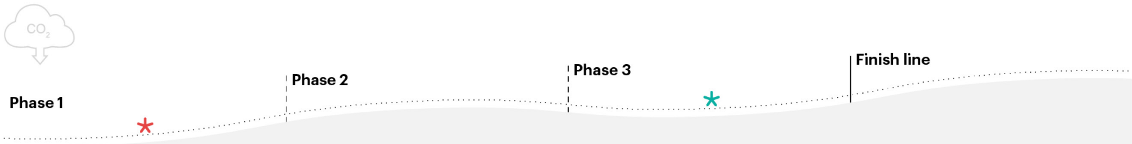
* 2023: The ACES Delta project in the United States, at 100 GWh, began construction for electricity storage with US government financial support.
* 2017: The world's largest hydrogen storage facility at a scale of around 400 GWh entered operation in the United States but is unproven for frequent cycling.

Criteria. Scale: 200 GWh storage capacity or higher. **Period:** Facility in operations for 6 months or more. **Other:** Injections and withdrawals of 10 GWh or more each.

Emissions reduction

The first **half-a-million tonne CDR** plant

CO_2 removed from the atmosphere by a single facility using a non-photosynthetic approach and in a way that is reasonably expected to have a permanence of over 10 000 years.



2024: One-sixth of the total capacity of Swiss company Climeworks' Mammoth project entered operational commissioning in Iceland, aiming to reach a rate of 36 000 tonnes of CO_2 removal per year during 2025 (TRL 7).

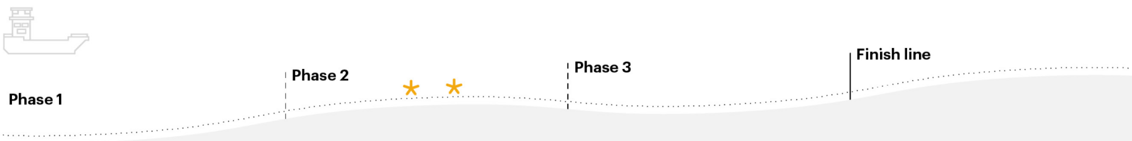
2023: Carbon Engineering and 1PointFive (two subsidiaries of US company Occidental Petroleum) started construction of the STRATOS project at a capture scale of 500 000 tonnes of CO_2 per year in the United States, towards operation of the first 250 000 tonnes CO_2 per year capacity in 2025 (once the total capture capacity is commissioned, the scale of CO_2 removal will depend on how much of the captured CO_2 is sent for permanent storage with appropriate monitoring).

Criteria. Scale: 500 000 tonnes of CO_2. **Period:** Cumulative over 12 consecutive months. **Other:** Must be verifiable according to a dedicated regulatory regime. Must be additional.

Emissions reduction

First **freight ship powered by a carbon-free fuel**

A one-way ocean-crossing of over 6 000 km relying on a fuel that does not contain any carbon for at least 75% of fuel needs.



2025: Mitsui E&S, a Japanese company, entered the test phase for a 60-bore dual-fuel ammonia engine from German firm MAN Energy Solutions to be installed aboard a 200 000-deadweight tonne bulk carrier with a view to commercialising 70- and 80-bore versions by 2026.

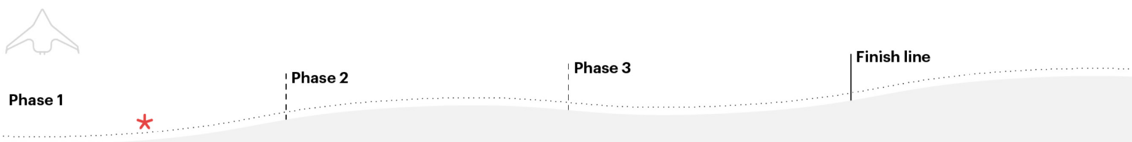
2024: Swiss company WinGD began testing a 72-bore single cylinder ammonia engine and has taken orders for a series of 210 000 deadweight tonne bulk carriers (TRL 7).

Criteria. Scale: A vessel with a 72-bore or larger engine. **Other:** Capable of carrying over 100 000 deadweight tonnes.

Technological spillover potential

First **blended wing body passenger aircraft**

A safe flight of 500 km or more in a blended wing body aircraft that reduces the energy consumption of flying.



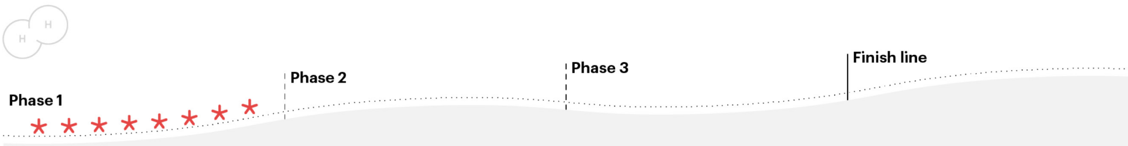
2024: US company JetZero reached agreements with component suppliers for a demonstration aircraft with the aim of beginning test flights in 2027 (TRL 4).

Criteria. Scale: Designed and furnished to carry 50 or more commercial passengers.

Technological spillover potential

The first commercial-scale **low energy intensity ammonia** production

Ammonia produced from water with an energy intensity of 25 GJ of energy input per tonne of ammonia produced.



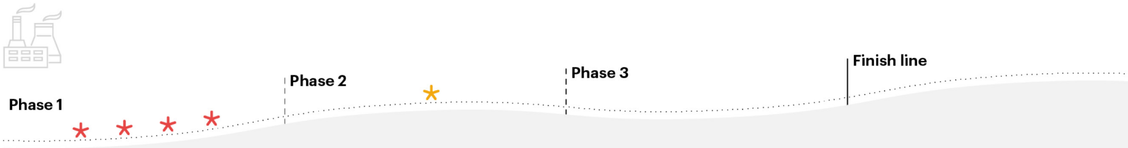
- 2024: Tsubame BHB, a Japanese start-up, received an order for a second 500 tonne electride catalyst plant for ammonia from hydrogen (TRL 5).
- 2024: Ammobia, a US start-up, raised USD 4 million to build a large pilot for a Haber-Bosch process for ammonia from hydrogen with ten times lower pressure than the industry standard (TRL 3).
- 2024: Nitrofix, an Israeli start-up, raised USD 4.5 million in equity and grants to build a pilot electrolysis plant for ammonia directly from water by 2026 (TRL 3).
- 2024: Jupiter Ionics raised around USD 8 million in equity and grants for research into its electrolytic process for ammonia production directly from water (TRL 3).
- 2024: Danish startup Nitrovolt, raised USD 3.8 million to build a test modular flow-cell reactor for ammonia from hydrogen at room temperature and low pressure (TRL 3).
- 2024: PlasNiFix, a Swiss start-up, received a grant to build a pilot plasma reactor for ammonia from hydrogen (TRL 3).
- 2024: Swan-H, a French start-up, raised over USD 1 million for R&D on its reactor design for ammonia directly from water (TRL 3).
- 2022: Trammo, a French ammonia trader, signed a contract to buy output from the US company ReMo Energy's 14 000 tonne pilot reactor for lower-pressure ammonia from hydrogen, which is under construction (TRL 4).

Criteria. Scale: 100 thousand tonnes or more globally using a single technology design. **Period:** Cumulative over 12 consecutive months. **Other:** Energy intensity calculated to include any intermediate steps, such as water electrolysis. Energy intensity calculated on a low heating value basis. For decentralised systems, small modifications in successive generations of installations count as a single technology design.

Emissions reduction

First **aluminium plant with very low direct emissions**

Primary aluminium produced with direct emissions from smelting of 0.2 t CO_2-eq per tonne or less.



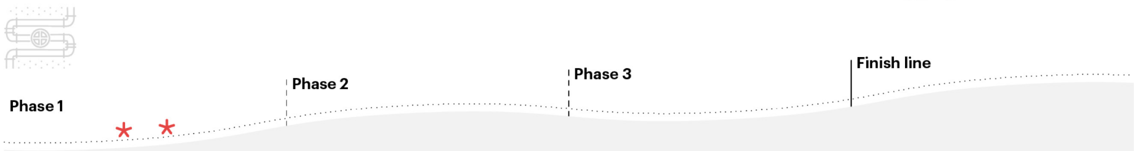
- 2025: British-Australian mining company Rio Tinto and Norwegian aluminium producer Hydro announced an R&D partnership on CO_2 capture from aluminium production (TRL 3).
- 2024: German aluminium producer TRIMET announced that it would construct a demonstration inert anode plant in Germany at a scale of roughly 100 tonnes (TRL 7).
- 2024: Rusal, a Russian aluminium producer, conducted the first-ever preheating and start-up of an aluminium reduction cell using inert anodes (TRL 7).
- 2024: Hydro published plans to achieve pilot-scale production for a process based on conversion of alumina to aluminium chloride by 2030 (TRL 3).
- 2024: Rio Tinto and US-headquartered aluminium producer Alcoa took final investment decision on a 2 500 tonne inert anode plant in Canada, supported by the Government of Québec, with first production targeted by 2027.

Criteria. Scale: 2 000 tonnes or more. **Period:** Cumulative over 12 consecutive months. **Other:** Any CO_2 storage must be verifiable according to a dedicated regulatory regime. Direct emissions from smelting included in the emissions intensity calculation.

Long-term energy security

Next-generation geothermal deployment in a place with no geothermal legacy

Supply to one or more customers of heat or electricity entirely derived from geothermal heat circulating in a fluid that has passed through fractured rock or closed-loop circuits in a country that has not previously generated electricity from geothermal heat at a scale of 100 MW or more on aggregate.



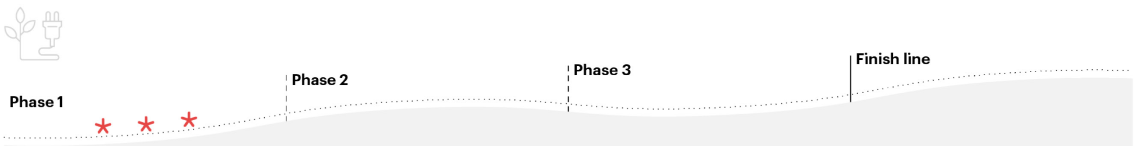
- 2023: US-based Fervo Energy started construction of a 400 MW enhanced geothermal system in the United States, which already has geothermal power (TRL 7).
- 2023: Canada-headquartered Eavor successfully drilled a two-leg multilateral well down to 5 500 metres and around 250°C, as required for a closed-loop system (TRL 5).

Criteria. Scale: One or more wells each feeding 10 MW of electricity output. **Period:** Uptime of greater than 75% over a period of 12 consecutive months. **Other:** For heat applications the temperature of supplied heat should be equal to or more than 150°C.

Technological spillover potential

Biochemical improvement of **CO_2 assimilation**

Demonstration in the field of an engineered photosynthetic pathway for assimilating CO_2 from the atmosphere and converting it to a potential bioenergy feedstock with a 35% higher mass yield than previously possible.



- 2025: Gigacrop, a US start-up, raised USD 4.5 million to use machine learning to improve enzymes, boost photosynthesis to use sunlight more efficiently and raise food and fuel yields.
- 2022: The Innovative Genomics Institute in California, United States, received USD 11 million to explore gene-editing approaches.
- 2022: The Max Planck Institute in Germany successfully inserted ECR enzyme, which has a turnover rate 20 times faster than RuBisCO (the principal enzyme that assimilates CO_2 in to the biosphere), into the genome of E-coli.

Criteria. Scale: Potentially scalable to 1 Gt CO_2/yr. **Other:** Can be in vivo or artificial. Improvement measured against a control in the same test(s) representing a best-in-class bioenergy crop not engineered using the tested method. Demonstrated between 400 ppm and 470 ppm CO_2.

6. Policy progress

Government support for energy technology innovation is a dynamic area of policy development. Policy makers across the world are both adapting their support measures to a changing technology environment and boosting efforts in line with ambitious policy goals, including seeking a competitive edge for their energy innovators in highly competitive equipment markets. On one hand, new mass-manufactured technologies can be brought to market relatively quickly and improved rapidly thereafter, and – on the other – dramatic changes to large-scale industrial processes are being applied in industries that have not significantly altered their technology basis for many decades. This situation, when combined with the ever-broadening suite of new energy-related technology options being developed across the world, calls for a tailored and flexible set of policy measures.[12]

This chapter presents policy updates, structured by the type of measure and stage of innovation that they target, from three main sources:

- The joint IEA-MI-OECD annual government survey of energy innovation policies.
- The survey of experts conducted for this report (see Chapter 1).
- The IEA energy innovation policy guide.

Governments are applying a range of policies to support energy innovation, tailoring support measures to the specific challenges faced by researchers and developers at different stages of technology readiness, market maturity and local conditions. These often combine multiple approaches to provide resources, reduce barriers and create incentives for innovators to invest. Dependable and rising market demand provides one of the strongest incentives to innovate. It is especially important for driving the incremental improvements to products and manufacturing that are often termed "learning-by-doing". It also attracts more attention to a sector's technology challenges and spurs disruptive new thinking in pursuit of market returns. However, most of the effective government policies that help to define and expand markets – including tax incentives, purchase grants, portfolio standards and environmental regulations – do not primarily target pre-commercial technologies. Such policies are well covered in other IEA reports and are not included within the scope of innovation policies in this chapter.

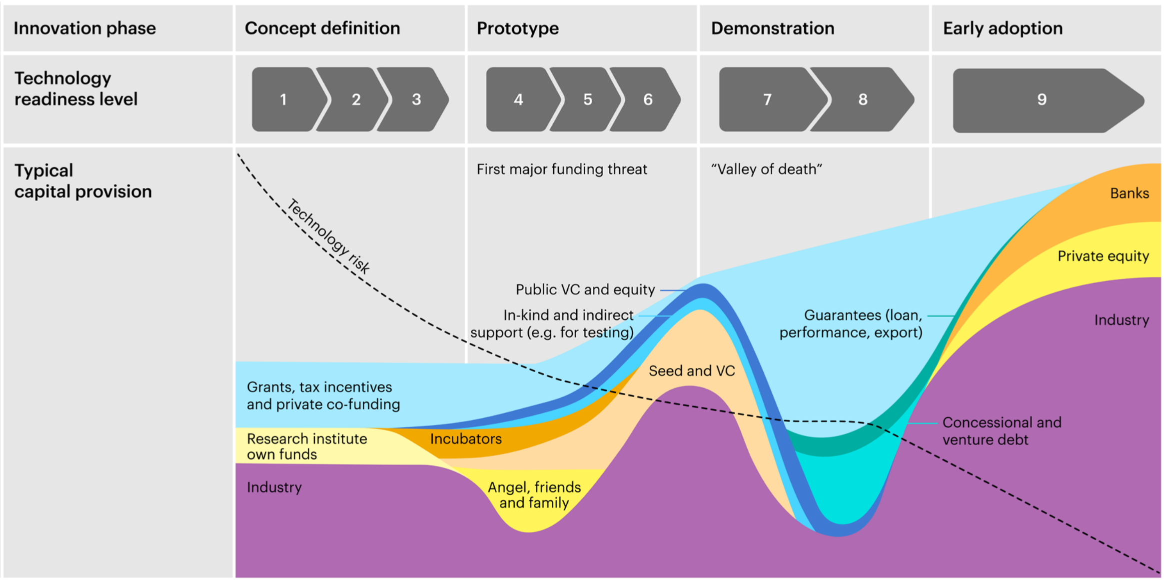
[12] This report follows a broad definition of innovation policy measure that includes any government intervention aiming to improve the chances that not-yet-commercial technology designs – which offer improved performance or lower costs compared with the existing leading solutions for their applications – will go on to attract widespread investment, shrink any remaining technological performance risk and accelerate progress towards societal goals. It includes funding programmes, but also spans strategic plans, targets, communication activities, regulations, finance, fiscal support, networks, intellectual property regimes and government-owned facilities.

The gathered examples show considerable government ingenuity, experimentation and learning, as evidenced by the diversity of new policy instruments introduced in the past 12-24 months. This chapter does not seek to anticipate any future policy changes that may come after March 2025, but acknowledges that there is currently some uncertainty about how the US government will seek to ensure its policies are aligned with changes to government priorities. Overall, the examples in the chapter mostly relate to funding and finance, including new financial tools such as equity, debt, loan guarantees or counter-guarantees. As shown in Chapter 3, many countries are expanding the scale of their grant funding for energy R&D and demonstration, but also putting in place other types of support for each of these phases of innovation. This chapter explores the variety of grant, financing and other measures in use, organised around three phases that are largely distinct from one another:

- Earlier R&D phases (technology readiness level [TRL] 1-5)
- First-of-a-kind pilots and demonstrations (TRL 6-8)
- Manufacturing and scaling up new products (TRL 9+)

The chapter also includes a section describing the important challenges and opportunities facing some emerging market and developing economies (EMDEs) that are seeking to build capabilities with more limited resources and experience. The chapter closes with a synthesis of proposed priority policy actions for the near term, covering types of instrument and underserved technology areas.

Representative changes in capital provision for energy technologies as they scale up



Note: VC = venture capital.

In a period of policy redesign and adaptation, a spirit of experimentation and experience-sharing is desirable. Policy evaluation is a necessary part of learning-by-doing in this area and, while publication of energy innovation policy audits is still not the norm for many governments, there are several examples of recent evaluations that offer valuable insights.

Lessons from recent innovation policy evaluations

Policy evaluation is a critical element in building public trust in government decision-making and ensuring the efficient and responsible use of public funds for energy innovation. While robust evidence can guide best practice in the design of energy innovation policies, such knowledge remains limited. Moreover, many different policies can directly or indirectly promote energy innovation, even if designed without an explicit goal for energy innovation, making it difficult to identify the impact of any single policy. In the highly interconnected energy innovation ecosystem, attributing cause and effect to specific policies is complex. Nevertheless, some recent evaluations provide relevant insights into the implementation and performance of different measures in practice.

Selected recent energy innovation policy evaluations

Country	Focus	Evaluator	Main findings
United States	Nuclear fusion	Government Accountability Office	Highlighted the need for public-private partnerships, research infrastructure development, and training.
United Kingdom	Innovation for net-zero	National Audit Office	Identified gaps in supporting later stages of innovation for net zero emissions technologies.
European Union	R&D strategy	European Court of Auditors	Recommended more integrated project databases and funding co-ordination between R&D programmes.
European Union	Hydrogen	European Court of Auditors	Recommended updating the Hydrogen Strategy to include targets based on analysis rather than aspirational goals.
France	Public energy R&D institution	Court of Auditors	Identified a need to address budget constraints related to the global pandemic, and an opportunity to expand engagement beyond traditional stakeholders.
Germany	Hydrogen	Federal Audit Office	Recommended measurable, time-bound targets, clear funding, and a monitoring system for the National Hydrogen Strategy.

Overarching energy innovation strategies

Many countries and regions set out strategic visions for R&D priorities and innovation objectives, which are typically renewed around every 5 years. Energy innovation strategies may be embedded in a broader innovation strategy or exist as a stand-alone strategy. In general, we find that energy is a top priority in many countries' strategic innovation plans. Energy innovation strategies are increasingly part of broader industrial strategies, designed to address concerns about the competitiveness of energy technologies.

Selected new or updated energy-relevant innovation strategies, 2022-2024

Korea

Korea's 5th Basic Science and Technology Master Plan (2023-2027) identifies 12 national strategic technologies, including batteries, nuclear power and hydrogen. It then sets out different co-ordination approaches including R&D strategies, strategic investments and plans for responding to new information and evaluating achievements. A complementary Special Act provides a legal framework for implementation.

European Union

The EU Strategic Energy Technology (SET) Plan was revised in 2023 to include new priorities such as skills, accelerating co-operation between the digital and energy sectors and minimising the use and increasing recycling of critical raw materials for energy technologies. The "Competitiveness Compass" was published in early 2025, outlining an EU Start-up and Scale-up Strategy to be in published in Q2/3 2025, for which the first call for evidence opened in February 2025.

Germany

The 2023 update of Germany's Future Strategy for Research and Innovation includes sustainability, climate neutrality and resilience within its six focuses. It describes a "learning strategy" which is intended to adapt to technological and economic changes, including through continuous monitoring, stakeholder engagement and attention to international competitiveness.

Austria

The Research Technology and Innovation (RTI) Pact 2024-2026 operationalises the RTI Strategy 2030 and defines strategic research and innovation policy priorities to achieve its energy goals. In accordance with Austrian Research Funding Act, the RTI Pact represents the link between the RTI Strategy, funding and implementing organisations with a total budget of around USD 5.3 billion.

The Netherlands

In 2023, the Netherlands consolidated different focus programmes into five core missions that provide a framework for aligning funding across innovation phases within a given sector. The mission dedicated to the energy transition sets sub-objectives for power generation, industry, mobility and the built environment.

Finland

Business Finland, a government institution, upgraded its pilot programme on the Zero Carbon Future to become one of its five missions in 2023. The goal is to channel about 50% of its roughly USD 800 million annual R&D funding to these five areas.

Malta

Malta's National Research and Innovation Strategic Plan 2023-2027 outlines missions for green and digital transitions.

China

In 2024, the National Energy Administration issued its Guiding Opinions on Energy Work, which describes how innovation is expected to support energy security and grid stability, as well as the growth of non-fossil energy supplies. The guidelines highlight R&D in nuclear power, smart grids, energy storage, renewables, hydrogen and efficient coal use.

Thailand

Thailand's National Science and Innovation Plan 2023-2027 identifies electric vehicles (EVs) and battery assembly as priorities for competitiveness within regional supply chains.

Some strategic innovation documents are pitched towards subsets of energy technologies, such as fuels, or critical minerals.

Selected new or updated energy-focused innovation strategies, 2023-2025

India

India published its National Green Hydrogen Mission in 2023. While this does not contain any specific targets for technology progress, it sets out expectations and funds for early deployment of technologies, including dedicated budgets for more immature technologies such as biomass-based hydrogen production. A public-private partnership framework for R&D is foreseen.

United States

As part of its Energy Earthshots Initiative, created in 2021, the United States announced targets in 2023 for clean fuels and products. These targets set out a 2035 goal for emissions reduction and 2050 targets for market share.

Canada

In 2023, Canada continued its Challenge programme (started in 2019) with a new challenge on AI-enabled platforms for critical materials discovery that will provide funding for projects aligned with the 2022 Critical Minerals Strategy. A further challenge on the application of AI to improve the productivity of cleantech manufacturing is planned for 2025.

Brazil

In 2025, Brazil's National Energy Policy Council updated its R&D and innovation guidelines for the allocation of resources by its electricity and oil & gas regulators, adding carbon capture and storage (CCS), reduction of fugitive methane emissions, energy efficiency, biogas from waste and wind energy as new priorities.

General support to energy innovation ecosystems

Effective national systems of technology innovation are underpinned by strong connections among researchers, investors, policy makers and potential users. The connectedness of information can be viewed as the critical "infrastructure" underpinning the innovation ecosystem and, like other infrastructures, it is a public good that governments are well-placed to oversee. Government policies can help ensure the knowledge arising from research and other projects flows as freely as possible. They can also help to ensure that a lack of personnel and skills is not a hindrance to innovation, and raise public understanding of new technologies.

Selected new policies for enhanced knowledge management, 2022-2024

United Kingdom

In 2024, a grant was awarded to a consortium to establish a virtual centre of excellence to connect stakeholders and share expertise relating to the use of AI for industrial emissions reduction.

Canada

Canada's Innovation Cluster programmes on advanced manufacturing and ocean energy include funding to support training, collaboration and the development of tools and test beds.

European Union

The European Commission has established several initiatives aimed at reinforcing energy innovation ecosystems. These include the European Innovation Council Trusted Investors Network. (established in 2024), the InvestEU Advisory Hub, the Heat Pump Accelerator Platform and the Battery 2030+ initiative.

Brazil

Brazil's System of Hydrogen Laboratories (SisH2-MCTI), established in 2022 within the scope of the Ministry of Science, Technology and Innovation (MCTI), is a network of laboratories with open access for users from the public and private sectors. It supports technical services, entrepreneurship and international connections.

Support during earlier R&D phases

Government support is often crucial for researchers working on new ideas and testing products up to the scale of a small pilot plant. This stage of the innovation process can take many years, represents a high-risk use of capital and may be difficult for the private sector to justify. This is especially true for small and medium-sized enterprises, including start-ups, that are considering clean technology concepts for which the public benefits could be large but near-term market signals are weak. The most commonly used instruments at this stage are R&D tax incentives, grants to researchers and funding for research institutions, but other tools, such as inducement prizes, are increasingly being tested.

Grants: non-repayable upfront funding

Grants are typically awarded via calls for proposals that take place within a multi-year programme that sets the priorities, budget envelope and evaluation procedures. Grants for research institution projects typically cover more than 80% of costs, while private sector participation typically requires an equivalent co-funding rate of up to 100%. Many of the updates from the past 12-24 months represent new calls rather than new programmes. When comparing different national programmes. the technology scoping of calls in North America tends to be narrower than in Europe, while some Japanese calls are very tightly defined around one specific option.

Selected new or updated grants for earlier R&D phases, 2023-2024

Japan

Japan's Green Innovation Fund was launched in 2021 as a means of providing research teams with funding for up to 10 years, providing more certainty compared with typical grant durations of 2-3 years. Regular monitoring of interim project targets allows companies to access more funds if they progress well. The overall budget is equivalent to USD 18 billion. In 2023 and 2024, calls were announced in emerging technology areas, including floating wind, perovskite solar PV, ammonia-fuelled ships, hydrogen use in steelmaking, next-generation aircraft and next-generation motors.

Canada

The 2024 calls under the Energy Innovation Program included battery industry, early-stage carbon capture, utilisation and storage (CCUS) concepts, clean fuels and industrial fuel switching.

United States

The United States has a wide-ranging set of grant programmes, including Small Business Innovation Research and Small Business Technology Transfer, which together provide around USD 300 million per year for energy R&D by SMEs. In 2024, the Advanced Research Projects Agency–Energy (ARPA-E) issued calls in the areas of Quantum Computing for Chemistry, AI and autonomous laboratories for industrial catalysts, fusion energy materials and geothermal power from deep superhot reservoirs.

The country also launched the 2024 Decadal Challenge within the Energy Storage Grand Challenge framework to issue small sums quickly to external innovators to support the identification and definition of key opportunities.

European Union

The Horizon Europe programme is the primary framework relevant to energy R&D. In 2024, nearly 100 calls for proposals were issued in areas related to energy and climate, including for aviation (aiming for a reduction of non-CO_2 emissions and contributing to the overall goal of a 30% fuel burn and CO_2 reduction by 2035), shipping electrification, HVDC power transmission cost reduction, and non-lithium batteries. The EU Clean Hydrogen Partnership issued calls in 2024 under its distinctive structure that pools funding from the European Commission and participating national governments, which together formed an annual budget of over USD 120 million in the same year.

Australia

The Australian Renewable Energy Agency (ARENA) Advancing Renewables Programme is notable because it is continuously open to applications, rather than operating time-limited calls. The priorities evolve over time, and in 2024 focused on hydrogen and the transition to low-emissions metals.

Slovenia

Slovenia is using EU funds for a programme that co-finances long-term scale research and innovation collaborative programmes at TRL 3-6. Two projects started in 2024, in the areas of hydrogen, batteries and industrial emissions.

Norway

In 2024, Norway committed the equivalent of up to USD 120 million over 8 years to establish eight new Environment-Friendly Energy Research Centres. Led by research institutions in consortia with the private sector, the centres will undertake long-term research in areas such as CCS, power grids, hydropower, shipping, metallurgy, solar and batteries.

Spain

The National Programme on Green Algorithms allocated around USD 280 million over 2023-2025 to foster R&D on the energy use of AI and the use of AI to improve energy efficiency.

Austria

Austria launched a grant programme for the transformation of industry in 2023. It offers the equivalent of USD 350 million in total until 2027 to support R&D, including demonstration projects, which are eligible for up to around USD 5 million each.

Belgium

In 2024, the approximately USD 25 million of calls under Belgium's Energy Transition Funds (a programme launched in 2017) focused on marine renewables, including offshore grids and flexibility in the power system. Projects are eligible for up to USD 5 million and higher cost shares are offered for lower TRL levels.

United Kingdom

Calls under the UK Net Zero Innovation Portfolio in 2024 included direct air capture, space-based solar, AI and small modular nuclear reactors. The portfolio has a budget envelope of approximately USD 1.3 billion.

Funding for nuclear fusion R&D and demonstration

Nuclear fusion has the potential to bring significant long-term benefits to society but has very high development costs that cannot be recuperated in full within the timelines typically expected in the private sector. There is a strong argument for using public funding to meet the costs of this research and doing so internationally, to the largest extent possible. Grant funding for fusion research is growing worldwide, largely directed to tokamaks, and with rising funding for stellarator designs. In 2024, **Germany** launched the Fusion 2040 programme, committing around USD 400 million over 5 years to advance fusion research, including stellarator technology, to complement its participation in ITER*. In early 2025, the **United Kingdom** pledged the equivalent of USD 525 million to develop a prototype tokamak fusion power plant. The **United States** increased the budget for their Fusion Energy Sciences programme to USD 790 million in 2024 (30% of which was for ITER), including for stellarator R&D, and also additionally allocated USD 690 million for laser inertial confinement fusion research. **China** is estimated to have allocated around USD 1.5 billion to fusion research in 2024, focusing on tokamak projects such as the Experimental Advanced Superconducting Tokamak and the China Fusion Engineering Test Reactor.

Although modest compared to the large R&D and demonstration investments in fusion, in 2024, the **European Commission** awarded three SOFT Innovation Prizes – biannual recognition prizes – to developers of nuclear fusion technologies, with the highest prize set at about USD 55 000. Unlike traditional grants, these prizes acknowledge past achievements without stipulating how the recipient spends the money. Such prizes help to raise the profile of the sector, highlight progress and recognise excellence in research.

* The International Thermonuclear Experimental Reactor (ITER) project aims to demonstrate that a fusion plasma can produce ten times the thermal power injected into it, using a tokamak design. The European Union committed around USD 6.6 billion to ITER for 2021-2027, providing about 45% of the funding, with the rest coming from India, Japan, Korea, Russia and the United States.

Access to research infrastructure

Governments often provide critical support to innovators by enabling access to cutting-edge R&D and testing facilities, often at government-owned premises. This can significantly reduce barriers to technology development for smaller research institutes and SMEs, and maximises the use of publicly funded infrastructure.

Selected new or updated policies for access to research infrastructure, 2023-2025

United States

The US Technology Commercialization Fund Open Voucher Call 2024 offered USD 2.1 million in 1-year vouchers of up to USD 100 000 each to cover access to certain national laboratory facilities. The country also operates 28 Office of Science user facilities at national energy laboratories, granting access on a competitive basis, and its American-Made Challenges initiative offers vouchers for laboratory access and expertise to competing teams.

California's public and private testbed resources are co-ordinated under the CalTestBed Network, which provides voucher programmes for low-emissions energy entrepreneurs. In 2024, the network awarded vouchers to 12 California-based start-ups, granting them access to testing facilities.

Canada

In 2025, Canada expanded its Clean Energy Siting Program to support fusion, hydrogen, battery storage and clean fuels. This builds on a programme operated since 2018 through which the National Research Council laboratories have offered a 40% discount on labour fees to SMEs.

The federal laboratories CanmetENERGY, CanmetMATERIALS and CanmetMINING offer support to SME technology developers. In 2024, calls were launched with a budget equivalent to USD 33 million for in-kind support for R&D projects at these laboratories under the Critical Minerals Research, Development, and Demonstration Program.

European Union

The European Commission provides open access to some of its Joint Research Centre research infrastructure.[13] A 2025 call aims to support the synthesis of nuclear materials for Generation IV nuclear power. The European Research Infrastructure Consortium (ERIC) helps co-ordinate access to pan-European research infrastructure as a single point of entry. Since 2023, CERIC-ERIC, which grants free access to energy materials research facilities in central Europe, added new fuel cell, electrolysis, and battery storage testing. In 2024, ECCSEL ERIC, which helps with access to over 100 CCUS research facilities, launched a funding call for Italian research access in 2024. In 2023, the MARINERG-i PP project began preparing a network of European testing facilities for offshore renewable energy for 2030.

The EU-funded ERIGrid 2.0 project facilitates access to 21 physical laboratories for smart energy research via quarterly calls for applications for laboratory vouchers, and 10 virtual facilities. The final application window closed in 2024.

[13] It does so via two types of calls: "relevance-driven", which are open to universities, research institutions and SMEs, require users to cover only variable costs associated with infrastructure use (nuclear research can have free access in some cases); and "market-driven", which require payment of full costs, usually by larger companies.

Access to high-performance computing and testing for AI-related R&D

There are high expectations for AI to accelerate energy technology R&D by enabling faster simulations, optimising complex screening of large data sets and running automated experiments (see Chapter 8).

For very computationally intensive tasks, access to computing capacity can be a bottleneck or high cost for researchers. Some countries own or co-ordinate high-performance computing facilities, which can be much cheaper than cloud-based services if they have high utilisation rates. The **European Union** High-Performance Computing Joint Undertaking has a budget of around USD 8 billion (2021-2027) and provides access to pre-exascale and petascale supercomputers. Its recent calls have been for large-scale capacity applications. By 2026, 13 new "AI factories" will provide preferential access to innovative start-ups and SMEs, with energy as a key focus area. The High-Performance Computing for Energy Innovation programme in the **United States** has offered up to USD 400 000 per industry-led project, as well as offering expertise from the national energy laboratories. In 2024 its calls focused on manufacturing and materials. In **Japan**, the High-Performance Computing Infrastructure system connects supercomputers and data storage at universities and research institutes. Its ongoing calls have recently included energy-related topics.

Governments are also creating facilities where researchers can validate their proposed applications of AI beyond the laboratory. The **European Union**'s 2023 Sectorial AI Testing and Experimentation Facilities (TEF) initiative is one such example. In **Denmark**, the CitCom TEF enables start-ups to test AI solutions in power, mobility and connectivity, and since 2024, the European Commission has allocated grants for creating additional TEFs focused on energy applications, including grids, hydrogen, and buildings.

Innovation inducement prizes to stimulate research excellence

Innovation inducement prizes provide incentives for researchers to be the first to reach a certain milestone and claim a financial reward. They are increasingly being explored for energy R&D because their technology-neutral approach relies less on the preconceptions of ex-ante evaluators and potentially opens funding up to more diverse technology options. In addition, having several different prize levels allows different technological approaches to be rewarded at different stages and generates learning about each one. In theory, inducement prizes can be less complex to administer, but in practice are often operated in stages and combined with smaller grants or access to facilities, which adds to the administration required. However, these combinations of instruments are often necessary to overcome the fact that researchers have to invest in R&D upfront and carry the risk of not being among the winners.

Selected new or updated energy innovation inducement prizes, 2024-2025

United States

In 2024, the American-Made Challenges programme, active since 2018, launched new energy technology prizes. Among them, the Commercial direct air capture (DAC) Prize has a budget of USD 100 million, and prize levels of up to USD 3.4 million for the carbon dioxide removal (CDR) Purchase Pilot Prize and up to USD 12 million for the Commercial DAC Pilot Prize. Other prizes cover manufacturing energy infrastructure technologies (a USD 5 million maximum prize) and grids cybersecurity (a USD 0.2 million maximum prize). The multi-stage prizes include laboratory vouchers and access to networks of support for winners of each stage.

Canada

Impact Canada Challenges have been used to attract innovators to high-priority energy technology problems. The last energy challenge, which concluded in early 2025, was for advanced, rapidly deployable oil spill response solutions.

European Union

Since 2019, the European Commission has piloted several prizes, including one from the European Innovation Council that awarded the equivalent of USD 5 million to the developer of a prototype system for synthetic fuel production in 2022.

In 2024 there was a new round of the European Statistics awards, including a third-round on nowcasting for oil, gas and electricity with a maximum prize equivalent to USD 5 500.

Germany

The Federal Agency for Breakthrough Innovation, SPRIN-D, offers inducement prizes through its Challenge Programme, a multi-stage competition in which participants receive initial funding, with further support awarded to those who advance to the next stage. Successful teams can receive up to several million euros of funding. The Carbon-to-Value Challenge on DAC was completed in 2024, while the Long-Duration Energy Storage Challenge is to be awarded in 2025.

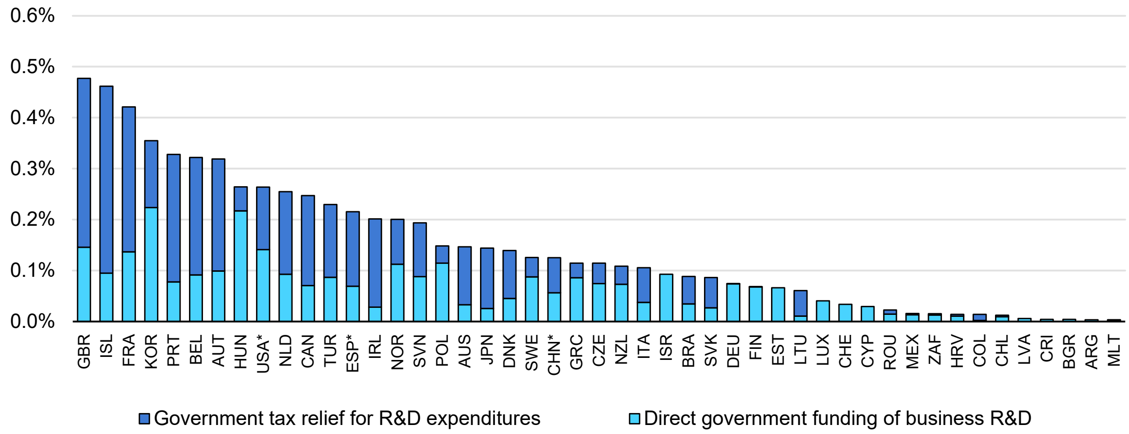
Spain

In 2024, a hackathon to improve predictive algorithms for optimising hydropower resources was organised.

R&D tax incentives

While not typically targeted to energy technology innovation, tax breaks for R&D activities are estimated to account for around 55% of total government support for business R&D across OECD Member countries. The share of R&D support through tax incentives has increased since 2000. In 2023, 33 out of 38 OECD countries, 23 of the 27 EU Member states and countries including Argentina, Brazil, China, South Africa and Thailand offered tax incentives for R&D expenditure at central or sub-national government level. Currently, no country gathers and publishes statistics on the tax credits claimed by companies active in energy technology areas. An exception to the technology-neutral approach is Italy's National Transition Plan 4.0 in 2020, which included increased tax credits for investments in R&D for "green and digital" projects.

Direct government funding and government tax support for business R&D per country as a share of GDP, 2021



Notes: * denotes that data on sub-national tax support are not available. The three-letter codes used on the x-axis are ISO 3166-1 alpha-3 codes for countries.
Source: OECD (2024), OECD R&D Tax Incentives Database.

Support for first-of-a-kind pilots and demonstrations

As technologies advance from smaller prototypes and pilot projects towards larger demonstrations that operate at scale in commercial conditions (i.e. moving from TRL 5 to TRL 9), they require much more capital at each successive stage, and each stage takes longer to be completed (see Chapter 4). Without being able to provide performance guarantees it is difficult to attract low-cost private capital for such projects, and promoters without large balance sheets often rely on government grants or hand over a share of their company ownership in return for equity investment. Governments have developed some funding tools over many years to give large first-of-a-kind projects the chance of crossing the "valley of death" if their technology is successful. However, with many governments looking to take on riskier, larger or more numerous projects in pursuit of competitiveness and pressing energy policy goals, new approaches and larger budgets have recently been announced. In addition to financial support, governments can also foster innovation at this stage by ensuring the enabling conditions for testing, demonstration and interacting with regulators.

Grants: non-repayable upfront funding

In recent years, the budgets committed for demonstration-stage energy technology projects have increased dramatically. Awarding and disbursing grants for large pilot and demonstration projects typically follow similar processes to those for R&D projects: commit budget, issue call, evaluate applicants, sign contracts, transfer money in stages against reported milestones and criteria. Governments are working to streamline approval processes, recognising that the lengthy timelines from application to final decision can lead SMEs and joint ventures to exhaust their working capital. For example, the European Union launched a public consultation in March 2025 on a new Clean Industrial Deal State Aid Framework to speed up and simplify approvals. Flexibility is also valuable for governments, as projects costs and technology assumptions can change during the course of these long processes.

Selected new or updated grants to support first-of-a-kind pilots and demonstrations, 2023-2025

United States

In 2024, the United States launched several new programmes for energy technology demonstration: the Generation III+ Small Modular Reactor Program (USD 900 million), Carbon Capture Demonstration Projects Program (USD 1.3 billion), Regional Direct Air Capture Hubs (USD 1.8 billion) and the Long-Duration Energy Storage Pilot Program (USD 100 million). A USD 6.3 billion funding opportunity was announced in 2023 under the Industrial Demonstrations Program and projects have been awarded in steel, cement, chemicals and refining, aluminium and process heat applications. While some projects under these programmes have already signed contracts, the future of others remains to be confirmed following the change of government in early 2025.

To smooth the scale-up path for promising technologies, the United States also launched a USD 50 million per year SCALEUP Ready programme to support pilot-scale projects (USD 5 million to USD 20 million) for technologies previously funded at R&D level by ARPA-E.

Canada

Canada launched several calls in 2024 and 2025 on mining, including a call of around USD 30 million for critical minerals pilot and demonstration projects under its Critical Minerals Research, Development and Demonstration Program, and a Mining Decarbonisation Demonstration call under its Energy Innovation Program. To aid learning, investment tax credits for CCUS projects that exceed specified cost thresholds are conditional on the developers making public regular “knowledge sharing reports”.

Japan

For dedicated support to innovators seeking to demonstrate their technologies abroad, **Japan** has a programme entitled International Demonstration Project on Japan’s Technologies for Decarbonisation and Energy Transition, which was launched in 1993 and had a budget equivalent to USD 30 million in 2024. Since 2023, it has supported a hydrogen-fired gas turbine demonstration in Germany.

Australia

Under Australia's Driving the Nation Program two calls worth a total of around USD 100 million have been launched to support the demonstration of heavy-duty EVs (2024) and charging infrastructure roll-out (2023).

France

The France 2030 Strategy contains a goal to allocate half of the budget (equivalent to around USD 60 billion) to low-emissions technology areas. Two calls for industrial projects are expected in 2025, one for brownfield projects requesting more than about USD 22 million but excluding hydrogen and biomass, and one for projects seeking to mitigate more than 1 kilotonne CO_2 equivalent (kt CO_2-eq) per year and requesting less than USD 33 million of support.

Sweden

Sweden's *Industriklivet* (Industrial Leap) initiative, launched in 2018, supports research, pilot and demonstration projects including bio-based CCUS. It has a budget equivalent to USD 130 million in 2025.

Impact Innovation was jointly created in 2023 by the Swedish Energy Agency, Swedish Research Council for Sustainable Development, and Swedish Innovation Agency. In 2024, it launched a Net Zero Industry programme and a Sustainable Metals and Minerals Supply programme, each backed by around USD 9-15 million for a call for start-ups.

India

India's National Green Hydrogen Mission, announced in 2023, has a budget equivalent to USD 175 million for hydrogen pilot projects, including in steel, mobility and shipping. In 2024, the government awarded grants to the first three projects in the steel sector.

European Union

The EU-Catalyst Partnership between the European Commission, European Investment Bank (EIB) and Breakthrough Energy Catalyst, a manager of private and philanthropic funds, awarded its first projects (for hydrogen-based fuels and long-duration energy storage) in 2023. Through early co-operation to provide complementary public grants and private finance (grants, debt or equity), the partners can reduce overall financial risks and speed up project development.

There are examples of governments funding R&D and demonstration projects using proceeds from levies on energy consumption, carbon pricing, energy company revenues, natural resource royalties or the liquidation of legacy assets. This dedicated reallocation of funds can help build support for such fiscal policies and provide long-term budget visibility for energy R&D and demonstration.

Selected grants for R&D and demonstration projects using earmarked levies

European Union

Since 2020, the EU Innovation Fund has supported large-scale energy demonstration projects with funds from sales of European carbon credits. While the scope has recently been broadened to allocate more of the funds to manufacturing scale-up, the 2023 call (USD 5 billion) included USD 220 million for pilot projects larger than USD 2.7 million each, and the Horizon Europe 2024 call included USD 22 million for the demonstration of advanced biofuels and synthetic fuels for transport, and USD 41 million for wave energy. In return for public funding, the project developers and European Commission commit to sharing knowledge from the project.

The European Commission has an earmarked annual budget for innovation projects that derives from the liquidated assets of its predecessor European Coal and Steel Community. In 2023, a project in Poland was funded to demonstrate methane emission reductions in coal mining.

Brazil

To fund its policy goals in the area of hydrogen, the Brazilian electricity regulator, ANEEL, issued a call (with a budget equivalent to USD 210 million) for large pilot projects within the scope of funds it collects from electricity utilities, which are mandated by law to allocate between 0.5-1% of their revenues to R&D.

Chile

Chile funds innovation projects using hypothecated fiscal income: revenues from the lease of state-owned mining sites are channelled to the national development agency (CORFO). In 2024, a USD 14 million call focused on lithium mining and secondary extraction of cobalt and rare earth elements.

Equity finance, including venture capital

Innovators aiming to develop their new products within dedicated start-up companies typically raise much of the capital for large pilot and demonstration projects as equity. The availability and cost of venture capital varies between regions and has traditionally been much more accessible to growth-stage companies in the United States. In countries with less developed venture capital systems, governments sometimes inject public capital as a means of stimulating private co-investment (See Chapter 3). Sometimes this is via public venture capital funds and sometimes by capitalising private venture funds, which may blend funding sources. Overall, public funds of varying types are estimated to be involved in 12% of all venture capital deals in Europe, with levels exceeding 20% in some countries, including Belgium, Ireland and Sweden. Outside Europe, the level of public funds is estimated to be just 3%. One downside of equity, however, is that it is a “dilutive” type of finance, which means that companies must hand over part of the value of their company in return for capital.[14]

Selected new or updated public equity funds focusing on energy, 2023-2025

European Union

The European Union, via the EIB’s European Investment Fund, launched the Cleantech Co-Investment Facility in 2024. It plans to allocate around USD 220 million over 4 years for equity co-investments aligned with EU climate and other environmental objectives.

The European Innovation Council STEP Scale Up scheme, launched in 2024, offers around USD 11-33 million in equity investments for larger projects, and focuses on digital technologies, clean technologies, and biotechnologies.

The European Innovation Council Accelerator (launched in 2021) has a 2025 budget of USD 55 million for Breakthrough Innovations for Future Mobility, and can offer convertible loans as well as equity.

France

In 2022, France launched the second round of the SPI fund, allocating the equivalent of USD 1.1 billion over 5 years to support innovative industrial projects. The fund provides equity investments ranging from USD 5 million to USD 163 million. In 2023, it invested in an EV battery maker.

Spain

In 2024, Spain's Institute for Diversification and Energy Saving allocated the equivalent of USD 110 million to acquire minority stakes in energy start-ups or special purpose vehicles (up to USD 11 million or a 20% stake per investment). In 2025, the venture fund of the Centre for the Development of Industrial Technology, which invests in start-ups and funds, some in the energy sector, backed a solid-state battery company and a critical minerals recovery technology firm.

Germany

In 2023, Germany established its DeepTech & Climate Fonds with around USD 1.1 billion, managed by the national development bank to co-invest in long-term ventures. In 2024, it supported a Li-ion battery recycling company and a nuclear fusion company, among others.

Finland

In 2023, Business Finland Venture Capital launched the Angel CoFund, with the equivalent of over USD 30 million to co-invest USD 54 000 to USD 325 000 in seed-stage start-ups in Finland. In 2024, it invested in a company developing a tool to help manage electricity supply for electrolysis

[14] Another type of equity finance that could be relevant to pilot and demonstration projects is project equity, a type of infrastructure finance that gives the investor a stake in the project but not the promoters. However, it is currently rarely used for energy demonstration projects as infrastructure funds tend to wait until after the demonstration stage before investing in new types of projects (see Chapter 3).

Norway

Since 2017, state-owned climate investment company Nysnø has invested in start-ups and allocated capital to other low-emissions nergy and climate-focused venture funds. In 2024, it invested the equivalent of USD 4.7 million in a company developing shore power systems for vessels.

Estonia

SmartCap, Estonia's state-owned venture capital fund, directly invests in start-ups and also invests in other venture funds. Its Green Fund initiative has a focus on environmental challenges, and invested the equivalent of USD 12 million in an electrolysis technology developer in 2025.

Australia

Australia's Clean Energy Finance Corporation has committed over USD 520 million to several national venture capital funds for energy technologies since 2016, including the Clean Energy Innovation Fund and Powering Australia Technology Fund. In 2024, equity investments included a Li-ion battery recycling technology developer, a company aiming to produce hydrogen from organic waste, and a lithium extraction technology developer.

Canada

Since 2023, the Canada Growth Fund has committed the equivalent of over USD 1.7 billion to 11 companies via a mix of equity and debt. Accelerating the deployment of hydrogen and CCUS are among its headline strategic objectives.

China

In early 2025, China announced plans for a government-backed venture capital fund of around USD 140 billion to support technology start-ups, including a focus on renewable energy.

Loans, including venture debt

Provision of debt by governments to projects or companies can have two benefits for innovators scaling up technologies: if the loans have concessional interest rates or extended repayment periods, they lower the cost of capital and thereby offset some of the technology risk. They also provide a strong signal that the project has passed government due diligence, reducing risks for co-investors. In addition, debt is a "non-dilutive" type of finance, which means that companies do not have to hand over part of the value of their company in return for capital. Some countries have sovereign wealth funds, public pension funds or state-owned banks that provide debt, but there are a variety of mechanisms around the world.

Selected new or updated government-backed debt for first-of-a-kind and demonstration projects, 2023-2025

European Union

The EIB offers loans for first-of-a-kind projects, either directly to large companies or via financial intermediaries for SMEs. Several loans in 2024 were for energy projects: the equivalent of USD 700 million for offshore power transmission; USD 550 million for direct lithium extraction; USD 275 million for advanced biofuels and upgrading with electrolytic hydrogen; and USD 100 million for a 5th generation heating and cooling network. In 2024, it also launched the Sustainable Investments (InvestEU VD) Lending Envelope equivalent to around USD 550 million of risk capital, with three out of nine focus areas related to energy.

As the ability of smaller companies to access affordable debt to sustain operations between successive large funding rounds varies between countries[15] and has been a notable challenge in Europe, the EIB has made targeted efforts to build a venture debt credit line that is appropriate for energy start-ups. In 2024, the EIB provided venture debt to Germany-based INERATEC for a synthetic fuel plant, to US-headquartered Rondo Energy for power-to-heat storage projects in Europe, to US battery material developer Graphenix Development (GDI) for a silicon anode demonstration plant in Germany, and to German company Sunfire for the development of solid oxide electrolysers.

Nordic & Baltic countries

In 2023, the Nordic Investment Bank approved a strategy to allocate the equivalent of USD 325 million to energy transition projects, backed by the European Union. In 2024, it signed a 7-year loan of around USD 50 million for hydrogen-powered and electric boats; and 12-year loans of around and USD 60 million for hydrogen-based steel production (alongside investment by the EIB).

Brazil

The Brazilian National Development Bank (BNDES) approved the equivalent of USD 12 million for an efficient onshore wind turbine prototype project in 2023 and also launched Mais Inovação, a programme that supported record funding for industrial innovation in Brazil in 2024, including for a cellulosic bioethanol demonstration project. Also in 2024, BNDES and the Brazilian Funding Agency for Studies and Projects (FINEP) launched a call for sustainable aviation fuel projects, offering a total of around USD 1.1 billion in grants, equity and debt.

United States

The Massachusetts Clean Energy Centre (MassCEC), a state economic development agency, can grant up to USD 1.5 million of venture debt to start-ups.

[15] The EIB estimates that venture debt represents only about 3% of the value of annual venture capital transactions in Europe, compared with 15% in the United States, where it is more readily available from private banks.

Facilities and environments for testing

The barriers to successfully testing a new energy technology at scale can be lowered if facilities with standardised and high-quality equipment are available, thereby avoiding much of the time, costs and risks of building new pilot or demonstration units from scratch. For technologies for which testing requires engagement with consumers or the wider public, there are large benefits from centrally co-ordinated "living labs" of real-world project participants. In addition, governments can also address regulatory issues facing innovators. Navigating international, national and local regulations requires levels of time and resources that are often only available to large companies. In some cases, regulatory frameworks that do not foresee certain applications of technologies need stress-testing before the regulations can be updated. This section considers policies for the provision of test facilities, living labs and "sandboxes" for regulatory experimentation.

Selected new or updated public testbeds and living labs, 2023-2025

United Kingdom

In 2024, new funds were committed to the European Marine Energy Centre to help the not-for-profit test facility to support tidal energy arrays.

Funding was announced in 2024 for a facility designed to test, validate and certify wind turbines with blades of up to 150 metres in conditions that replicate those at sea.

United States

The United States supports a commercial-scale testing facility for electricity transmission line technologies that announced a successful test in 2024 of a robot-applied coating that can safely increase current-carrying capacity.

In 2025, a USD 101 million call was launched for the development of five test centres for CO_2 capture, removal and conversion.

Utah FORGE is a dedicated US-government-led field site for the development and testing of enhanced geothermal technologies. Technology developers apply for access via calls. In 2024, FORGE partners reported the successful connection and energy transfer between two wells, a key step towards commercialisation.

Austria

In 2023, Austria launched its Living Laboratories for 100% Renewable Energy initiative, which aims to establish up to five initiatives by 2025 to develop, test and validate approaches that could enable fully renewable energy supplies.

Belgium

In 2022, VITO, an R&D institute funded by the Flemish government, opened "living labs" for testing energy technologies in housing estates.

China

China's 2025 Government Report announced a second round of projects to create test facilities for technical, societal and regulatory experimentation related to emerging energy and digital technologies (so-called national carbon peak pilot projects, zero-carbon parks and factories).

Growth in the number of regulatory sandboxes for energy technologies

"Regulatory sandboxes" are temporary frameworks that allow for certain regulatory exemptions or special freedoms to facilitate the testing of new products and services in a safe and conducive way that does not expose test projects to the full costs and risks of regulatory compliance, while providing the necessary safeguards to protect consumers and the energy market. They also facilitate structured co-operation between innovators and regulators, who provide legal guidance. They have emerged as a means of enabling regulated energy suppliers – such as electricity network operators – to undertake innovation projects that would normally be considered too risky under their mandate to minimise costs and risks. They first emerged in the energy sector in the United Kingdom and the Netherlands in 2015, and the concept spread to countries including Singapore shortly thereafter.

Recent developments include:

- In 2024, **Brazil's** electricity regulator approved a regulatory sandbox for demand response, targeting large consumers, building on its Tariff Sandbox to test new tariff models for low-voltage consumers, launched in 2023. It launched a public consultation on a voltage control sandbox in 2024.
- In 2024, **Denmark**'s first regulatory test zone (a structure foreseen in legislation from 2019) started operating with exemptions from electricity regulations to test solutions for integrating high shares of variable renewable energy at an industrial cluster.
- In 2024, **Moldova** enacted a law to grant 7-year exemptions for complex trials, extendable by 5 years.
- In 2024, the **United Kingdom**'s gas and electricity regulator updated its framework to a four-tiered approach and launched a project to develop guidance for applications of AI.
- In 2024, **Spain** launched a second regulatory sandbox on voltage control. Payments and exemptions from reactive power charges were offered to large consumers to absorb excess reactive power and prevent voltage surges.
- In 2023, **Australia's** energy regulator granted its first 30-month trial waiver to a project deploying smart meters to enhance load management services.
- In 2023 in **Canada,** Ontario Energy Board's Innovation Sandbox (from 2019) was updated with the power to provide temporary regulatory relief. It launched a call for pilot projects funded with USD 1 million from compliance penalties.

Support for manufacturing and scaling up new products and processes

Successful demonstration of a technology at scale still leaves a major challenge of scaling up to competitive commercial deployment. Costs usually remain high due to limited experience, meagre economies of scale, immature supply chains and, in the case of technologies with environmental benefits, under-pricing of externalities. This cost gap, coupled with a lack of familiarity among potential customers, discourages private sector involvement. To create an initial market and drive early adoption, governments can use public procurement, offtake contracts, standardisation and regulatory measures. To help new technology products to reach these initial markets, investments in manufacturing can also be supported.

At this stage, the dependability of market demand is a much more critical factor than at previous stages. While they are not direct innovation policies per se, regulatory design and harmonisation, standardisation, portfolio standards, purchase subsidies and pricing of externalities are examples of market creation measures that must be aligned with the scope and timing of innovation policies.

Publicly backed offtake contracts

Offtake contracts are firm agreements from customers to buy future output and they can significantly reduce upfront investment risks associated with production facilities for (or using) a new technology. By reducing the risk that output will not find a buyer at a sufficient price, the costs of capital for the builder of the facility will be lower. In the electricity sector, governments have often created or supported offtake contracts with commitments of more than 10 years, and they increasingly seek to ensure value-for-money by using auction mechanisms to select recipients.[16] "Contracts for difference" (CfD) that limit government funding[17] to the incremental costs above a variable market benchmark can be especially appropriate for earlier-stage technologies. The benchmark represents what a customer would ordinarily be willing to pay in the market for the product, and some governments arrange separate auctions for more mature and less mature technologies, which need different levels of "top-up" above the benchmark. This approach exposes technologies at the scale-up stage to competition between one another but shields them from competition with more established technologies. In 2024, several government-run auctions were opened or concluded for earlier-stage energy technologies, mostly in Europe. In the United States, production tax credits provide a similar type of support by guaranteeing a fixed payment for each unit of eligible output.

[16] They typically use pay-as-clear or pay-as-bid settlement mechanisms.
[17] Or, in some cases, the cost that governments require to be passed on to consumer bills.

Selected new or updated energy-related publicly backed offtake contracts, 2023-2025

Sweden

In 2025, Sweden held the first auction for bio-based CCUS, which awarded a 15-year contract worth around USD 1.9 billion to a cogeneration plant project.

United Kingdom

The United Kingdom increased the CfD budget for less-established technologies in its annual power sector auction from a level equivalent to around USD 45 million to more than USD 340 million, including some ringfenced budget for tidal and floating wind energy. As a result, a large floating wind project was able to secure a 15-year CfD at a price 2.3 times higher than standard offshore wind projects.

France

In 2024, France opened a dedicated floating wind auction for three 250 MW floating wind 20-year CfDs.

Italy

Italy issued a decree in 2024 that carved out dedicated funding for 20- or 25- year CfDs for thermodynamic solar panels, geothermal, floating solar, tidal and wave power.

European Union

In 2024, the European Commission launched the second European Hydrogen Bank auction with a budget of around USD 1.3 billion for 10-year offtake contracts (from the Innovation Fund), including USD 1.1 billion for projects across all end-uses and a dedicated USD 220 million for maritime uses. Applicants evaluated by the European Commission can directly get privileged access to support from EU Member states (so-called Auctions-as-a-Service), a model to which Austria (around USD 440 million), Spain (around USD 300 million to USD 440 million) and Lithuania (around USD 40 million) have committed funding.

Germany

H2Global is a CfD auction for hydrogen projects established in 2022, and it is notable for using a double auction whereby bidders for contracts to buy hydrogen supplies and bidders for contracts to supply hydrogen (or ammonia, methanol or synthetic kerosene) offtake may be shortlisted separately. An intermediary signs 10-year CfDs that make up the difference between the prices offered by the two sides with public money. In 2024, the Netherlands joined the initiative and a USD 430 million CfD contract was awarded for ammonia supply from Egypt to Europe. In 2025, a second auction worth USD 2.7 billion was launched.

Japan

In 2024, Japan launched a 15-year CfD auction for low-emissions hydrogen and its derivatives, backed by up to USD 20 billion in government funding. The reference price will vary depending on the intended end-user.

In 2024, Japan introduced a strategic tax incentive programme to support domestic production in critical sectors such as EVs, green steel, green chemicals and sustainable aviation fuel. Companies investing in these areas are eligible for up to 40% of their corporate tax liability over 10 years, with the credit rate decreasing after 8 years. Unused tax credits can be carried forward for 4 years.

India

The Solar Energy Corporation of India (SECI) launched auctions in 2024 for hydrogen offtake contracts that had a budget equivalent to USD 270 million, including a portion ringfenced for biomass-based production, but the latter was ultimately undersubscribed. Also in 2024, SECI ran an auction for 10-year contracts for 750 000 tonnes per year of low-emissions ammonia, which it will supply to fertiliser manufacturers. The country's Production Linked Incentive (PLI) schemes for low-emissions energy technologies follow a similar process to support solar PV and battery manufacturing, but with criteria for domestic value addition to qualify for financial support or higher payments.

Australia

Australia's Hydrogen Headstart program allocated offtake contracts worth around USD 2.6 billion in 2023 and 2024 to bridge the gap between costs and expected sales prices for hydrogen from renewable electricity.

United States

The Inflation Reduction Act 2022 included the 45X Advanced Manufacturing Production Credit, which guarantees a credit for each unit of domestic production of eligible solar PV, wind energy, battery components and critical minerals. The credit, which can be sold to other firms if the producer's tax bill is not high enough to use it, is scheduled to decrease from 2030 and will be phased out by the end of 2032. Other tax credits were also introduced to create early markets for energy technologies, including for hydrogen production (45V), CCUS (45Q) and transport fuels (45Z).

Public procurement

As an alternative or complement to arranging long-term offtake contracts with individual firms, governments can buy goods and services supplied using early-stage energy technologies. This can take the form of more stringent criteria for public procurement in terms of environmental performance, or the use of direct purchases to create a market that did not previously exist at scale, such as for high-quality carbon dioxide removal (CDR) credits. As public procurement sets a standard for any supplier that can win a contract, it also encourages innovation towards more competitive products. As an indication of the scale of investment that public procurement can unlock, it accounts for roughly 12% of global GDP, with a similar share observed across countries of different income levels. Globally, the public sector buys nearly half of the cement and, in some countries, up to one-quarter of the steel produced each year. However, public procurement tends to be decentralised, both internationally and within countries, which poses co-ordination challenges, especially for aligning aspects such as environmental criteria. The OECD's Working Party of the Leading Practitioners on Public Procurement promotes good practices and policy coherence in this domain.

Updated public procurement initiatives for innovative energy-related products in selected countries, 2023-2025

United States

The United States announced a State Buy Clean Partnership in 2023 whereby 13 states committed to prioritise lower-carbon materials in state-funded construction projects.

India

In 2024, India's Energy Efficiency Services Limited, a state-owned company, closed a tender for buying 100 000 induction cookstoves in pursuit of economies of scale and lower costs.

Canada

In 2023, Canada created a Low Carbon Fuel Procurement Program to buy 200 million litres of low-carbon fuels for the federal aviation and marine fleets. In 2024, the programme's budget was expanded from around USD 92 million over 8 years by adding around USD 7 million for the procurement of CDR credits.

The country has a Buy Clean approach to support low-carbon building materials and designs in line with its Greening Government and Green Buildings Strategies.

Portugal

In 2023, Portugal committed to incorporate innovation criteria relating to sustainability into public procurement.

Spain

In 2023, Spain established a Public Innovation Procurement framework to increase purchases of innovative technologies, including near-commercial and pre-commercial products (by testing prototypes in government applications). All its public procurement already has environmental and energy efficiency criteria.

European Union

In 2025, the European Commission announced that it will review its public procurement framework in 2026 to integrate sustainability, resilience and European preference criteria in strategic sectors.

Grants and tax incentives: non-repayable funding

As with R&D and larger pilots and demonstration projects, governments use grants to reduce the costs faced by firms when building their first factories or production facilities for products that are new to the market. In some countries, investment tax credits operate similarly to grants because they can be claimed before construction begins and, if the project developer's tax bill is not large enough to make use of them immediately, sold at a discount to other companies. A key difference between grants and investment tax credits is that grants are typically awarded via competition among applicants for a fixed budget, whereas tax credits are available to any firm that meets the eligibility criteria.

Selected new or updated grants and tax incentives for manufacturing and scaling up, 2023-2025

Canada

In 2024, Canada introduced a Clean Technology Manufacturing Investment Tax Credit, providing a 30% credit on the capital cost of eligible low-emissions energy technology manufacturing investments, receivable only after production has begun. The credit rate is set to decrease from 2032 and will be phased out by the end of 2034. Similar credits are available for CCUS and hydrogen.

European Union

Two calls under the EU Innovation Fund (see above) were opened in 2024, with its scope expanding to include manufacturing plants as well as technology demonstrations. One call covered low-emissions energy technologies in general, including manufacturing (budget equivalent to around USD 2.6 billion) and one was for EV battery cells manufacturing (budget equivalent to around USD 1.1 billion). Applications evaluated favourably but not funded by the European Commission can be used as a basis for streamlined State Aid reviews (so-called Grants-as-a-Service).

In 2025, within the framework of its Connecting Europe Facility for infrastructure projects, the European Commission awarded a grant worth the equivalent of USD 700 million for building the first commercial offshore multi-terminal high-voltage direct current hybrid interconnector in the Baltic Sea. The facility can also award grants to early-stage hydrogen and CO_2 transport infrastructure.

Denmark

The Green Accelerator Facility in Denmark has provided seed funding for export projects in areas of sustainable technologies since 2020 and, in 2024, granted support for the Rebuilding District Heating in Ukraine project.

Australia

In 2024, Australia introduced its Battery Breakthrough Initiative, to fund domestic battery manufacturing with approximately USD 350 million, and its Solar Sunshot programme, to fund domestic solar PV manufacturing and innovation with more than USD 650 million.

Loans

Debt financing is generally required for large projects, even in cases where the project receives a substantial grant. This is especially true in the early stages of build-out of a new technology, before infrastructure investors are able to offer project equity and project debt. However, in some cases, scaling up a new technology with a first factory or production facility is hindered by a lack of access to affordable debt. This might be because the developer is perceived as a risky investment by private banks or because it has a high opportunity cost for capital expenditures in a portfolio that includes projects with shorter payback periods. Governments can offer concessional loans with below-market interest rates and more flexible terms, and these typically require less public money than grants. In emerging and developing economies this role is also played by multilateral development banks, as a means of unlocking private investment in projects.

Selected new or updated public debt finance for manufacturing and scaling up, 2023-2025

United States

The US Loans Programme Office approved loans worth USD 10.8 billion in 2024 for lithium-ion battery factories, lithium carbonate production, silicon carbide wafer manufacturing for longer-range EVs, and lithium-ion battery recycling under its programme for vehicle manufacturing loans.

European Union

The EIB agreed a loan worth around USD 700 million for a project aiming to build the world's first artificial offshore island for wind energy, and launched a new product worth over USD 325 million for loans to EU-based SMEs with eligible energy technologies.

Hungary

In 2024, Hungary announced a credit facility equivalent to near USD 100 million in total for support to geothermal drilling, which can carry high upfront risks.

Brazil

In 2024, Brazil's National Development Bank (BNDES) approved a loan worth around USD 7 million loan to a developer of biomethane from sugarcane waste and a loan worth around USD 90 million to a company deploying a technology that can avoid hazardous chemicals and waste production from lithium production.

Nordic & Baltic countries

In 2024, the Nordic Investment Bank approved a loan for an onshore wind farm from its credit facility worth USD 325 million that was established in 2023 for low-emissions energy projects.

Australia

Australia created a credit facility in 2024 for interest-free loans of up to around USD 10 million each to help lithium miners survive unexpectedly low prices.

Canada

Canada Infrastructure Bank aims to award credit worth around USD 7.5 billion in total to wind, solar, tidal, biomass, nuclear and energy storage projects. In 2022, around USD 750 million was provided to the country's first nuclear small modular reactor project. In 2023, around USD 35 million was awarded to build the country's largest battery storage facility.

Loan guarantees, counter-guarantees and export credits

Guarantees are another means by which governments can reduce the cost of capital for an infrastructure investment related to an early-stage technology. They can be especially effective for SMEs without a strong track record who wish to borrow from lenders that do not have extensive knowledge of the type of project. Guarantees act as an insurance for a private lender by accepting certain hard-to-assess risks related to project or technology performance. While governments must set aside capital to cover downside risks across the portfolio of guarantees, this is typically cheaper than providing either concessional loans or grants and can in some cases be very effective for unlocking private investment in new technology assets.

Manufacturers are often asked to provide major buyers with guarantees that provide insurance against non-delivery, underperformance or failure. As these guarantees can tie up 100% of the contract value for new market entrants in advance (compared with 20% to 30% for established suppliers), they represent a major liquidity problem for young firms and some established ones in developing economies. Government counter-guarantees can alleviate the need for suppliers to set aside these large sums and allow them to continue to invest in innovation. In general, the cost to the taxpayer is not high: only 0.2% of performance guarantees were called on between 2016 and 2022.

Selected new or updated guarantees for energy-related innovations, 2023-2025

United States

The United States pioneered the use of loan guarantees to support large-scale energy infrastructure projects through the Loans Program Office. In 2024, a USD 15 billion loan guarantee to Pacific Gas & Electric was issued to supports a portfolio of grid modernisation and innovation-related initiatives. In the same year, a USD 1.5 billion loan guarantee was issued to help recommission a nuclear power plant.

European Union

In 2023, the EIB created a guarantee facility worth the equivalent of near USD 5.5 billion for commercial banks offering guarantees to wind energy equipment manufacturers. The facility is indicative of how innovators might be helped to introduce new products, though it has not so far been used for innovative technologies. In 2024, nearly 80% of the total value was committed to nine banks. Plans have been announced to make more than USD 540 million worth of counter-guarantees available for low-emissions energy technology production in 2025.

France

France's Strategic Projects Guarantee supports energy and raw materials projects. In 2024, it had the equivalent of USD 2.2 billion available to fund loan guarantees of up to 80% for investments above around USD 11 million. As of 2025, it can support French companies undertaking projects in France, in addition to its previous focus on French companies in projects abroad.

In 2023, France launched a fund worth around USD 210 million for guarantees against deep geothermal drilling risks in projects with scales of around 30 MW.

A growing role for export credit in energy technology innovation internationally

Public export credit agencies and export-import banks help exporters to finance investments in support of contracts with overseas buyers. By offering debt or guarantees, they reduce the cost of capital for international equipment suppliers. For technologies at an early stage of market penetration this can facilitate the scale-up of manufacturing, including by reducing risk perception for private sector co-investors, and can also reduce overall project costs for large-scale demonstrations in other countries. In 2023, the international regulatory framework for export credit was modernised to allow credit terms to be extended to 18 to 22 years for an expanded list of climate-related technologies. The revised framework now includes, among others, power transmission, energy storage, CCS, low-emissions hydrogen, and minerals and ores for energy, while also introducing greater repayment flexibility.

Between 2013 and 2023, the share of renewable energy in global export credit commitments to the energy sector increased markedly, rising from 9% to 42% for guarantees and from 5% to 39% for direct lending. The main beneficiaries were offshore wind and, more recently, electrolysers and related equipment.

- In 2024, CESCE, **Spain**'s export credit agency, backed up to 50% of the USD 1.3 billion guarantee to Siemens Gamesa to help it service its more than USD 40 billion wind turbine order backlog and expand further.
- **Germany** backed Thyssenkrupp Nucera to supply electrolysers worth more than USD 350 million to the first gigawatt-scale project in Saudi Arabia, and backed Stegra's hydrogen-based steel project in Sweden.
- In 2024, the Export-Import Bank of the **United States** indicated its willingness to provide USD 104 million in debt financing for delivery of a first 20 MW nuclear microreactor for use in the United Kingdom.
- **Australia**'s export credit agency announced USD 533 million in debt financing to Arafura for a first-of-a-kind rare earths processing facility in Australia, and this helped unlock direct lending and untied loan guarantees from export credit agencies in Canada, Germany and Korea.

The challenge of innovation in emerging and developing economies

Emerging market and developing economies (EMDEs) have a major stake in technological change in the energy system, including through the innovations needed to underpin it. In recent years, energy, climate and development policies in many emerging economies have included ambitious innovation objectives for energy technologies. The economic opportunity is large, and strengthening energy innovation systems in these countries is important for achieving secure, affordable and sustainable energy systems globally. However, the statuses and forms of these innovation systems vary widely today.

EMDEs face multiple challenges to fully reap the benefits of this opportunity. The emergence of new technologies, led by mass-market solar PV, batteries and EVs, is bringing the economic opportunities of low-emissions energy into focus for governments, including in developing economies. Nurturing new technologies to maturity can create local economic prosperity, and new energy technologies will offer market opportunities for all economies in the coming decades. However, EMDEs face specific challenges to be overcome in order to take advantage of these opportunities, including constrained public budgets, competition between immediate social needs and longer-term innovation goals, a lack of cutting-edge research infrastructure, high costs of capital for risk-taking enterprises, weak intellectual property enforcement and small or uncertain domestic markets for innovative technologies.

As documented by IEA analysis, emerging economies have a wealth of innovation experiences to share, and all countries have much to learn from them. Many already have extensive experience in technology R&D and deployment, whether for energy or in adjacent areas, but it is rarely given the recognition and attention it deserves. Examples of global technology leadership in these countries are more plentiful than is often recognised, and include biotechnology in India, nuclear power in Argentina, synthetic fuels in South Africa, biofuels in Brazil, financial technology in Kenya, fertilisers in Morocco and building materials in Mexico.

In work with the Indian Institute of Technology, Delhi, the IEA notes key findings that demonstrate the strengths of energy innovation in 11 selected countries:

- Energy innovation has risen high up the policy agenda in developing economies, just as it has in advanced economies. The potential for industrial development and inward investment are key motivating factors, along with the need to boost energy security and respond to the climate challenge.
- Energy innovation outcomes are more easily achieved when they align well with national visions for economic and social development. In **India**, energy efficiency was boosted by the government’s priority of maintaining access to electricity for a growing population despite financial challenges for utilities.
- There are multiple ways to set innovation in motion. In **Kenya**, for example, a new cohort of producers of solar home systems were born from a funding programme for off-grid solar PV that rewarded innovative means of adapting services to local consumers’ needs.

- Institutional history exerts a powerful influence on policy choices. **South Africa**'s "just transition" policies have their roots in a long social and institutional history. Successful innovation policy interventions work in harmony with the existing policy landscape. Overall, the state typically plays a more prominent role in the energy sector than it does in advanced economies.
- Existing technical expertise can provide a springboard, including from adjacent sectors. For example, **Kazakhstan**'s energy technology plans promote areas that require transferable skills from the oil and gas sector. **Mexico** is building on its manufacturing expertise to enter technology sectors related to solar PV.
- There are demonstrated ways to make the most of limited resources. International co-operation – whether through financial support or knowledge-sharing – is a key feature, as is prioritisation of technology options that match local capacities. **Morocco** has developed tools and expertise for exploring potential technologies and identifying gaps to be targeted by policy.

Recent energy innovation policies in emerging and developing economies

In 2024, members of the Research and Innovation Working Group under Brazil's G20 Presidency co-operated on an energy technology innovation policy guide targeted towards governments and other stakeholders in emerging and developing economies. The guide shows that, while grants to research projects and direct funding of public research institutions remain the most widely used innovation policies, the range of measures adopted is much broader and includes roadmaps, financial instruments, knowledge networks and regulation of large companies. For EMDEs, policies often also feature capacity-building programmes, either for institutional capabilities or expertise relating to specific technologies. In addition, and of relevance to developing economies, the compilation of policies includes measures that encourage and reward domestic innovation without requiring deep pockets. These include participating in projects co-funded by more than one government; awarding prizes (including inducement prizes); facilitating access to government-led laboratory and testing facilities; establishing networks of researchers and users; knowledge-sharing; patent processing; and information campaigns.

Recent energy innovation policies in emerging and developing economies with a novel or particularly ambitious approach

South Africa

In 2024, South Africa unveiled a Higher Education Innovation Fund in partnership with the United Nations Development Programme to make entrepreneurship services available in the higher education sector in South Africa, with an emphasis on job creation and spin-off companies.

India

As part of its National Hydrogen Mission, launched in 2023, India has launched several instruments that can help domestic innovators to finance scale-up for technologies at the earliest stages of adoption. The SIGHT programme earmarks more than USD 500 million to be distributed to electrolyser manufacturers at a rate starting at USD 50 per kW produced, and reducing over the 5 years of the contract. The system is intended to help overcome the high cost of capital and reward manufacturers of more efficient products and those whose output is sold into local markets. It is coupled with simplified procedures, lower taxation and other types of business support. The programme also has a component that rewards hydrogen production, and a portion of this was reserved in 2024 for processes that use biomass, a more immature technology.

Since 2015, India has operated a network of Technology Business Incubators, which creates an independent channel for directing other policy measures to start-ups, allowing the incubators to choose how to use government funds to support start-ups with grants, loans or equity, and reinvest proceeds.

Kazakhstan

In Kazakhstan, since 2021, companies in the extractive industries must allocate at least 1% of their total annual income to energy R&D projects selected by the Ministry of Energy and the Ministry of Industry.

African Union

The African Union conducts the LEAP-RE mechanism with the European Commission to fund energy R&D and capacity-building projects of mutual benefit to Africa and Europe. It involves joint calls funded by African and European funding agencies, with an additional top-up from the European Union, and requires projects to have African and European partners, with the aim to create long-term partnerships among African and European stakeholders. The budget of the programme for the 2025 call is around USD 14.7 million.

Morocco

In 2021, Morocco's renewable energy innovation institute, IRESEN, refreshed its Green InnoBoost programme. It gave awardees the choice of receiving finance as a grant (with a requirement to pay royalties from resulting innovations) or as equity (whereby the future sale of up to a 20% stake could help IRESEN finance future activities). IRESEN also creates bank accounts for recipients to manage risks related to transferring money to young companies. Morocco also partnered with Côte d'Ivoire on a semi-tropical test centre for renewable energy.

Chile

In 2024, Start Up Chile, a programme of Chile's industrial development agency CORFO, launched its ninth call for start-ups, which is a rare example of a government-run business accelerator programme open to low-emissions energy innovators.

In addition, some dedicated policies have been established by advanced economies to support the energy innovation efforts in EMDEs:

- In 2022, the **United Kingdom** committed the equivalent of USD 80 million to launch a programme at the United Nations Industrial Development Organization that will be used to provide grants to demonstration projects in developing countries in the areas of critical minerals, hydrogen, smart energy and industrial decarbonisation.
- **Germany** launched a platform in 2022 that can connect projects in emerging and developing countries that aim to build local supply chains for hydrogen production from renewable electricity with grant and debt finance. In 2024 and 2025 it allocated its first USD 65 million to projects in Egypt and Morocco.

Recent energy innovation highlights in emerging and developing economies

Among the examples of recent energy technology progress gathered for this report, including via the survey (see Chapter 1), are several from domestic innovators in EMDEs:

- In June 2024, the world's largest cellulosic bioethanol facility was commissioned in **Brazil** by Brazilian company Raizen. It has a capacity of 82 million litres, of which 80% is already contracted. This technology has not yet been deployed successfully at commercial scale in other regions. In January 2025, the next plant received USD 190 million in concessional debt from BNDES, which also loaned USD 127 million since 2022 (including USD 35 million in 2024) to Eve Air Mobility, a spin-off from Embraer, a Brazilian aeroplane maker, for electric aviation R&D over the next decade.
- In **Kenya**, Octavia Carbon raised over USD 5 million to scale up its DAC technology, with some of the finance backed by advance credit commitments for future CO_2 removals in Kenya.
- Siam Cement Group in **Thailand** has become an early adopter of electrified thermal storage technology and also a component supplier to the technology developer Rondo Energy. In 2024, it began constructing a first heat battery for cement production at hundred-megawatt scale.
- R.Flo, a start-up in **Ukraine**, received funding in 2024 from the UK Government to install its 75 kWh, 6-hour long-duration iron redox flow battery at a Ukrainian power plant to prove its capabilities in challenging circumstances and shed light on whether it can achieve low costs for distributed, resilient storage.
- In **Ghana**, Kofa, a developer of battery-swapping systems for electric motorbikes, was awarded USD 7.9 million by the UK Government and Shell Foundation to deploy and test its latest technology.
- Ecosafi, an African start-up, launched an efficient new biomass cookstove for cleaner cooking in 2024, and was awarded USD 1.6 million from Norway and

Sweden via the Modern Cooking Facility for Africa to deploy it in several **sub-Saharan African countries**.

- The Research Centre for Greenhouse Gas Innovation at the University of São Paulo in **Brazil** applied for a utility patent for a new method of monitoring hydrogen production in electrolysers.
- AES Andes, a renewable energy developer from **Chile**, began the conversion of a coal-fired power plant to a 560 MW, (minimum 10-hour discharge time) molten salt thermal energy storage facility, a project whose development is supported by Germany.

In addition, technologies are being developed in other parts of the world to address the unique challenges and opportunities in EMDEs, often including testing and adaptation to the specific context through partnerships in EMDEs:

- Cella Mineral Storage, a US start-up developing CO_2 storage via mineralisation, is preparing two projects in **Kenya**, where the geological conditions are very favourable. One is in partnership with Octavia Carbon. A second project, announced in 2025, is with Sirona Technologies, a Belgian start-up.
- A team of researchers in Sweden has reported good results for a battery prototype that is based on zinc and lignin (from plants) that could have low cost and avoids the toxicity of widely used lead-acid batteries. Although it would have lower performance than Li-ion batteries, it may find a receptive market as an affordable and durable energy storage option for low-income countries.
- Husk Power, a company headquartered in the United States, developed a containerised minigrid system at their R&D centre in **India** that is being installed in less than a day in India and Nigeria, supported by Nigeria's Rural Electrification Agency, the EIB, the World Bank and the India Renewable Energy Development Agency.

Remaining policy gaps and priorities

The survey conducted for this report returned many good examples of policies that stakeholders believe are accelerating the pace of energy innovation around the world. However, respondents also highlighted some areas where more effort from governments and other stakeholders is needed to help tackle arising challenges. While many of the identified policy gaps are highly specific to a given country or technology, some are more generalisable and are summarised in this section.

- **Raise public energy R&D and demonstration spending.** Governments still have some way to go if they are to restore the levels of energy R&D spending per unit of GDP that were common four decades ago. If countries were to raise energy

R&D and demonstration spending to at least 0.1% of GDP, a level reached by IEA Members in 1980, during a period of concerns about energy security and price, (see Chapter 3), this would stimulate private sector co-funding, enhancing competitiveness and economic growth. Gaps in data availability – especially for non-grant data and for several major economies – prevent an accurate calculation of how close the world already is to this value and underpin the need for improving systematic data collection.

- **"Ensure that the overall level of public and private support remains stable in priority areas through economic cycles.** The macroeconomic environment since 2021 has not been supportive of innovators raising funds for high-risk, high-potential projects. Governments should continue to help researchers and entrepreneurs to access operating capital. With the exception of AI-related technology areas, there is no sign that investors' wait-and-see postures are yet giving way to higher risk appetites. If anything, inflationary pressures are now compounded by policy and trade uncertainties. Instruments including venture debt, bridging loans and other patient types of credit facility are useful developments where private capital is less available, including in Europe. Exploring how national and multilateral development banks can play a leading role in EMDEs will be important.
- **Co-operate to bring a global portfolio of large-scale energy demonstration projects to fruition**, with particular emphasis on large-scale projects in sectors where key near-zero emissions technologies are not yet at TRL 9. This includes aluminium, cement, steel, aviation and shipping (including fuel production), DAC and other forms of CDR. The Races to Firsts published in this report (see Chapter 5), and which will be tracked by the IEA, are one way to encourage progress alongside initiatives including Mission Innovation. International collaboration and public-private partnerships are vitally important, as sharing learnings from projects between regions and domains of expertise are key to accelerate progress. For each major technical challenge, a balanced set of projects that covers different technological, geographical, regulatory and market contexts would be an ideal outcome to minimise total costs.
- **Ensure that publicly funded research supports accessible training datasets for AI-driven R&D.** Without concerted efforts to build and co-ordinate dependable and accessible datasets, the world may not be able to grasp the full potential for AI to enhance energy innovation (Chapter 8). This risk concerns the discovery phase of materials used in batteries, solar PV, catalysts and CO_2 capture, but also the design and testing of new approaches to nuclear fusion, geothermal energy and high-efficiency air conditioning. Governments can also address potential inequalities in access to data and computing facilities that could lead to AI widening the gaps between advanced and developing economy research teams, rather than living up to its promise of narrowing them.
- **Support access to testing facilities and "living labs.** The jump in funding needs for developers of energy hardware when moving from prototyping to larger pilots and demonstrations can delay and thwart high-potential technologies. A large

share of these costs relate to the construction and operation of one-off testing facilities or field trials, which can in many cases be replaced with more durable and long-term infrastructure. Accessible R&D and testing facilities, whether publicly or privately funded, can significantly shorten the times to market for technologies including building energy management and virtual power plants, geothermal, long-duration energy storage, CDR and heat networks, among others.

- **Work to reduce bureaucracy and seek to align funding processes with innovators needs**, especially under intense international competition. Such efforts are already underway, especially for grant-funding processes that have long evaluation times and all-or-nothing outcomes. This chapter highlights some ways in which governments are creatively overcoming this well-known issue, including by operating permanently open calls and sharing evaluation processes ("grants-as-a-service" and "auctions-as-a-service"). Multi-stage prize processes that are tightly focused on key arising technology challenges, with the ability to launch the initial grant stages quickly, hold considerable promise. Above all, there is a major opportunity for governments to share experiences and increase impact by building on what has worked well (or not) elsewhere.
- **Tailor support to the innovation needs of each technology, including considering systemic barriers to uptake** from the outset. In some sectors, such as buildings, improved technologies for energy efficiency and demand response will be unable to make significant impacts unless there are also improvements in non-technical aspects, including how buildings are conceived and designed for their lifecycle. Adoption of new materials, equipment, controls and building methods requires support for designers to explore and integrate them, and for this to cascade into diffuse local supply chains. Many impressive engineering solutions become stuck at TRL 9 in such situations because social and behavioural norms must adapt before they can be widely adopted.
- **Stronger energy innovation systems in emerging and developing economies** can help modernise energy systems and drive economic growth. While many EMDEs have developed domestic technologies and policies, further efforts are needed to expand innovation capacity and leverage skills from other sectors. Active innovation co-operation, both among EMDEs and with advanced economies, can support technical capacity building, policy development and technology adaptation to local conditions, such as tropical climates. At the same time, EMDEs offer unique opportunities for scaling up some technologies that would benefit from plentiful renewable resources – including those for DAC, low-emissions hydrogen or near-zero emissions steel. Stronger energy innovation co-operation can foster new companies, build skills and address pressing challenges – such as energy access, clean cooking and mobility – while also supporting more resilient global supply chains.
- **Continue to seek ways of maximising innovation impacts from public investments** in first-of-a-kind projects. This chapter details the diversity of approaches being trialled around the world for loans, guarantees, auctions for

offtake contracts, prizes, equity stakes and knowledge-sharing. It will take time for formal evaluations to reveal their relative strengths and weaknesses, creating a strong case for governments and recipients to share policy experiences internationally as they are learned. Given the urgency of many countries' energy technology policy goals, attracting more institutional investor and multilateral finance to the early stages of scale-up will be important, and there are opportunities for co-operation on reducing regulatory and technical barriers.

- **Foster markets that give confidence in robust future demand** for the products of the most successful innovators**.** Competition between firms and regions is a major incentive for investments in manufacturing innovation, driving continual learning-by-doing. Government support – including public procurement, offtake contracts, regulatory design, standardisation and mandates – can all play a role in boosting competitiveness within a region, and internationally. Technologies such as nuclear SMRs, tidal power, CCUS, low-emissions fuels and materials are currently at the stage of benefiting from such measures. However, with energy technology policy now encompassing the manufacturing of clean technology equipment, attention to quality control, yield and supply chains during scale-up are new concerns for decision makers.

7. Focus: Innovation to improve diversity of battery minerals supplies

Modern batteries are set to be one of the cornerstones of future energy systems thanks to rapid innovation in the design and manufacturing of lithium-ion batteries over the past 30 years. The cost of lithium-ion batteries for electric vehicles (EVs) has fallen more than 90% since 2010, and the specific energy[18] of EV battery packs has more than doubled since the Tesla Roadster battery pack in 2006. The drop in battery prices is making EVs more affordable, and also helped the battery storage market to almost quadruple between 2022 and 2024,[19] enabling more renewable electricity deployment and more resilient power grids. Contributions to this astonishing rate of progress have been made by researchers, engineers and investors in countries all around the world, including through direct collaborations on research, product development and factory projects.

However, demand for the critical minerals that make these batteries possible is rising and substantial investments in new mines and refining capacity will be needed to produce the lithium, cobalt, manganese, nickel and graphite that they require. In 2023, lithium demand rose by nearly 30%, while demand for nickel, cobalt and graphite all saw increases ranging from 8% to 11%. Demand growth for each of these is primarily driven by EVs, which represent the largest single source of demand for lithium and a growing share of demand for the other minerals.

Where this capacity is located and where new capacity is built will affect the resilience of battery supply chains, which today are concentrated in a small number of countries and controlled by a limited number of stakeholders. For battery materials mining and refining, the shares of the top three producing countries remained high between 2021 and 2023. As of 2023, about 85% of lithium is mined in Australia, Chile and China, which is also where almost 65% of the lithium is refined (a further 25% is refined in Chile). Over half of nickel is mined in Indonesia, some of which is refined in China. Together, these two countries account for over 60% of nickel refining. The Democratic Republic of Congo is home to almost two-thirds of world's cobalt mining, though three-quarters of all

[18] Energy stored per unit mass, a key metric for many road vehicle and other applications. Energy density refers to energy stored per unit volume, a different but equally important metric, and is often used as shorthand for either metric.
[19] EVs remain the main driver of battery demand, accounting for 85% of total battery demand in the energy sector in 2024.

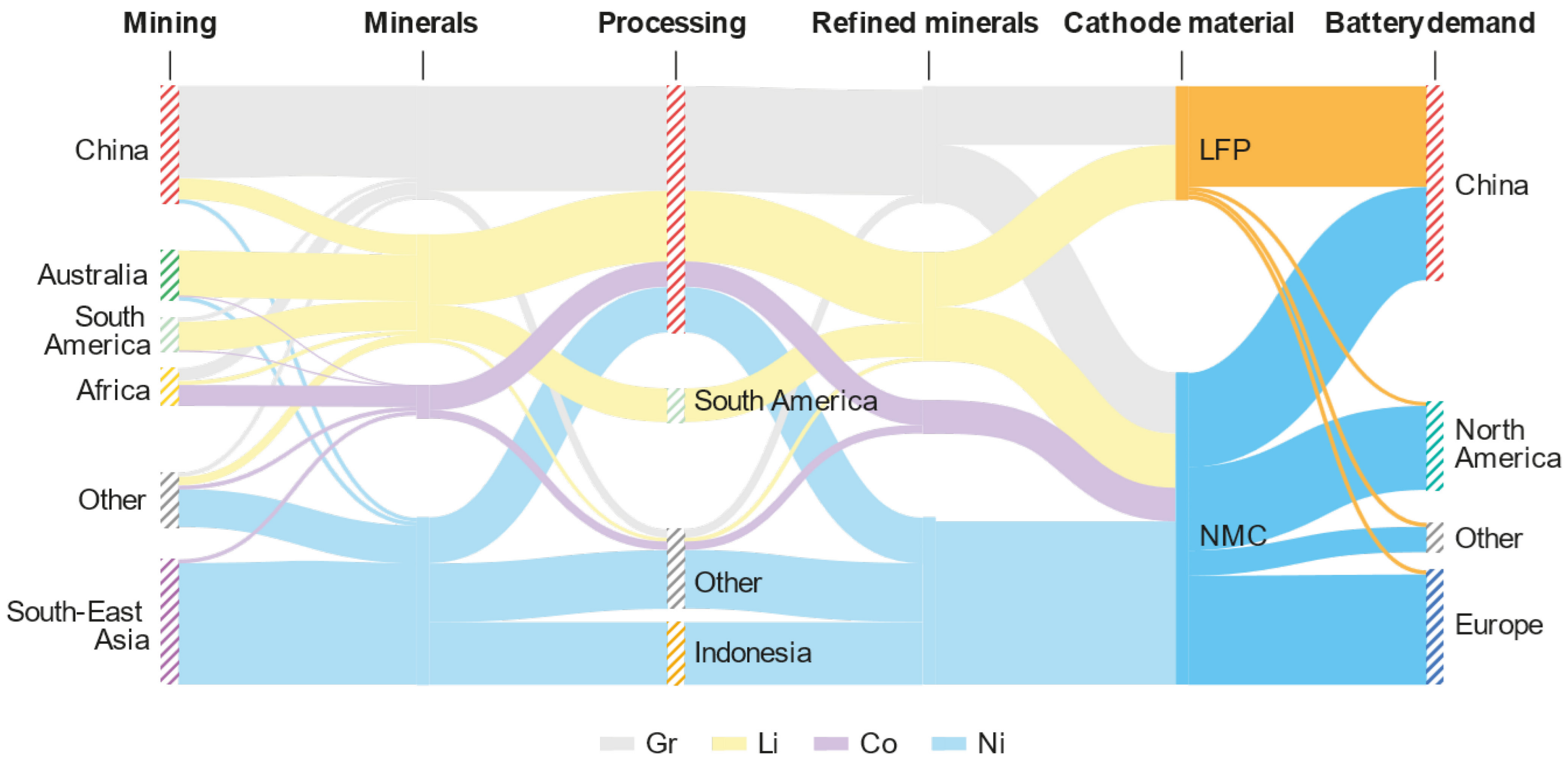
cobalt refining is in China. Graphite is even more concentrated, with both 80% of mining and over 90% of refining occurring in China.

This concentration is unlikely to change soon, with IEA analysis showing that some 70-75% of projected supply growth for refined lithium, nickel and cobalt through to 2030 will be from today's top three producers. For battery-grade spherical and synthetic graphite, almost 95% of growth comes from China. Chinese company ownership extends to much of the world's nickel and cobalt production, despite these minerals being mined elsewhere (e.g. nickel in Indonesia and cobalt in the Democratic Republic of the Congo). In addition, China is the leader in the processing and refining of all these minerals. These high levels of supply concentration make supply chains and routes more vulnerable to disruption, whether from extreme weather, trade disputes or geopolitics.

In recent years, various governments have sought to restrict or redirect trade in batteries and their inputs, and this pattern has continued into 2025, with China announcing restrictions on technologies used to produce graphite anodes, certain cathodes and their precursors, and direct lithium extraction technologies.

The turbulence of fast-growing critical minerals markets jeopardises the necessary investments in diversified mineral supplies. The IEA Energy Transition Mineral Price Index tripled between January 2020 and March 2022, and then relinquished most of the increase by the end of 2023. Lithium spot prices plummeted by 75% in 2023, and cobalt, nickel and graphite prices dropped by 30-45% due to a combination of new supplies and ample battery component inventories for the expected level of demand. While lower mineral prices are positive news for battery producers and consumers, mining companies invested less in new mineral supply in 2023 than in 2022, and some narrowly avoided bankruptcy. Insufficient investments in new supplies creates a risk of shortages as demand for critical minerals rises, especially given the long lead-times for mining projects. In the IEA Stated Policies Scenario (STEPS), announced mining projects would not be able to meet the growing demand for lithium and copper between 2030 and 2035.

Electric vehicle battery minerals' supply chain from extraction to end-use, by mineral value, 2023



Note: Gr = graphite; Li = lithium; Co = cobalt; Ni = nickel; LFP = lithium iron phosphate; NMC = lithium nickel manganese cobalt oxide. Flows are scaled based on the economic value of a mineral or the combined value of minerals used in the cathode or EV battery. All flows are represented on a material price term.

The case for strengthened innovation

Battery raw materials are unevenly distributed around the world, making it difficult to significantly alter the patterns of raw mineral supply to satisfy demand for existing battery technologies. Changes to patterns of refining and trade for these existing technologies are, in principle, feasible but would require large investments in new capital stock that the private sector would be unlikely to undertake alone, given the competitive position achieved by China. Battery mineral recycling and mineral extraction from alternative sources in locations that today have no production are either constrained by limited feedstock, high costs, or technologies that are not yet mature.

However, innovators working on technology development have the potential to improve the diversity, resilience, environmental impacts and costs of battery mineral supply chains. This work is of global importance to secure energy. Without commercialising different battery chemistries, or technologies to tap into different sources of mineral supplies, by 2030, the world would be on course towards a potential threefold increase in lithium demand compared to 2023. In addition, having a range of proven chemistries for EV batteries provides flexibility in supply chains that can respond to market tightness through substitution, and limit price spikes. Innovation – whether in chemistry or manufacturing – is also essential to ensuring battery prices continue to decrease even if there are supply chain constraints, including tariffs. Successful innovators that can deliver these technology improvements stand to access a large share of a battery market that is projected to reach almost USD 500 billion in 2035.

The five relevant areas of technology development include:

- **Reducing or changing mineral demand through shifts in battery chemistries.** Today's EV battery market is mostly divided between two types of lithium-ion cathode chemistries: lithium nickel cobalt manganese oxide (NMC) and lithium iron phosphate (LFP) batteries. Lithium nickel aluminium cobalt oxide (NCA) was previously widely used in EVs, particularly by Tesla, but has now fallen to less than 5% of the EV battery market. The share of LFP batteries, which use fewer critical minerals, increased rapidly between 2020 and 2024, reaching almost half of the EV battery market (on an energy capacity basis), largely driven by Chinese manufacturers. Innovation in LFP has therefore significantly reduced reliance on nickel and cobalt, and batteries that can sharply reduce lithium content are also getting closer to market.
- **Reducing mineral demand by minimising battery size and extending battery life.** Technology innovation can help to ensure that drivers are able to meet their mobility needs affordably with batteries that are right-sized for the task and remain fit-for-purpose for as long as possible, including via smaller EVs. This focus chapter does not examine the component technologies due to space constraints,

but it is an active area of research. Battery technology improvements and smart battery monitoring systems at the pack and cell level already help improve battery durability in cars, while logistics and town planning technologies that reduce the need for road transport altogether can also help reduce demand.

- **Reducing demand for newly mined inputs by reusing end-of-life batteries.**[20] When batteries that are retired from high-performance applications (such as electric trucks or cars) are repurposed for use in lower-performance applications (such as micromobility or stationary storage), or refurbished for reuse in the same application, it cuts demand for new batteries but also delays the re-entry of the constituent minerals back into new EV batteries through recycling. Improved technologies are needed to make the reuse of batteries as seamless, competitive and dependable as purchasing a new battery, the prices of which continue to fall.
- **Reducing demand for newly mined inputs by recycling end-of-life batteries and battery scraps.** As long as there is demand for the scarce materials found in batteries at the end of their useful lives, recycling those materials will help curb the extraction of newly mined inputs and the environmental damage that can accompany mining, while increasing the supply chain resilience of regions with limited access to battery minerals.
- **Diversifying and expanding mineral supplies by accessing alternative resource types.** There is considerable interest in technologies that can improve the competitiveness of extracting battery minerals from resources with less environmental impact or in a more diverse range of locations, such as lithium found in geothermal and oilfield brines as an alternative to geographically concentrated hard-rock ores and near-surface deposits.

The known technology pathways and their statuses are reviewed in the following sections. All of these pathways have the potential to play a role in future battery supply chains, and their competitiveness will vary between markets due to factors including local geology and regulations. However, the long-term competitiveness of the individual firms developing the finished technology products will depend on their integration into the overall technology and market landscape, as well as their capacity for incremental innovations in their products and manufacturing processes. Firms that are not vertically integrated into all supply chain steps might need to access preferential agreements and stay well aligned with the changing needs of a complex web of producers (of batteries or EVs), component suppliers, refiners and mineral producers (from virgin resources, scrap or end-of-life products) in order to remain competitive.

[20] Technically, these are “end-of-first-life” batteries.

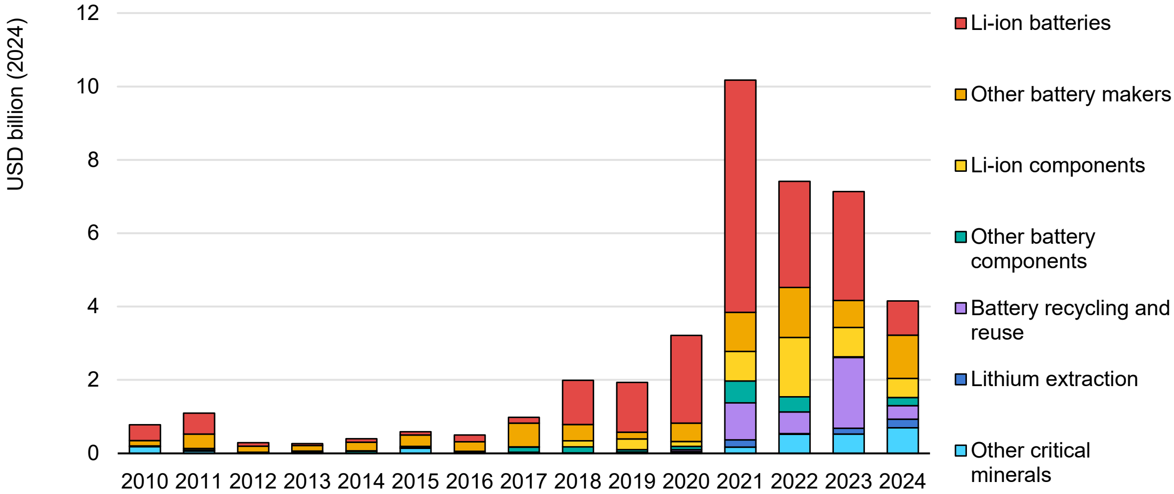
Battery innovation is not only about invention

The story of LFP cathodes illustrates how battery innovation is not only about the invention of new technologies but also about their competitive integration into a dynamic supply chain ecosystem. The LFP cathode represents around three-quarters of the Chinese EV battery market, double its share in 2020. Its more than 10% share in 2024 in the European Union – twice that of the previous year – surpassed the share in the United States. The LFP cathode was first identified in 1997 by researchers in the United States, and further developed in Canada and the United States through the early 2000s to overcome its initially low electrical conductivity. The first LFP cathode factory was opened in Canada in 2012 with support from the Canadian government. However, despite this origin story, LFP production in North America was not aligned with the preference of domestic EV makers for the longer driving ranges enabled by NMC chemistries. Due to tight control of LFP intellectual property, its rate of improvement slowed as scale-up stalled. However, Chinese firms had a more favourable intellectual property agreement for domestic LFP production and use, and they invested in further scale-up, attracted by its lower costs and avoidance of problematic cobalt and nickel supply chains. Today, nearly all global production is in China, where manufacturers have achieved a globally dominant market position, including through extensive expertise and innovation. These innovations include new cell formats, charging platforms, cell-to-pack and cell-to-chassis configurations, while R&D focuses on LFP battery processing, chemistry and optimised electrodes for longer ranges and faster charging.

Technology landscape

The full spectrum of innovation efforts to improve the performance of batteries for EVs and electricity storage is wide and expanding. This section focuses on a subset of that spectrum: technological developments that are intended to help diversify supply chains for critical minerals for EV batteries. This section does not cover technologies for general cost reductions in lithium-ion batteries – now largely driven by incumbent manufacturers, with equity fundraising for Li-ion battery start-ups in 2024 falling to 15% of its 2021 peak – nor technologies dedicated to battery storage, including redox flow and iron-air batteries. The latter technologies could, however, represent a source of diversification for battery storage applications, and are expected to be important to unlock longer duration battery storage. Additionally, it does not cover policy, business or logistics creativity for enhancing supply chain resilience.

Equity fundraising by electric vehicle battery start-ups, 2010-2024



Source: IEA analysis based on Cleantech Group (2025).

Batteries from non-scarce materials

Batteries comprise four main constituents – anodes, cathodes, separator and electrolyte. The cathode and anode[21] store lithium ions, from which the technology derives its name. The primary function of a separator is to prevent electrical short circuits, while the electrolyte enables the movement of lithium ions from the cathode to the anode during the charging mode, and vice versa during the discharging mode, enabling the conversion of stored chemical energy into usable electrical energy. Anodes, cathodes and electrolytes are today reliant on minerals that have concentrated supply chains or have experienced price volatility. These constituents can be considered separately, even though they are typically not fully interchangeable in a finished battery cell, i.e. any specific electrode (anode or cathode) and electrolyte is optimised for compatibility with the other constituents.

Anodes

Today's lithium-ion anodes are primarily made from battery-grade graphite, and more than 90% of graphite refining occurs in China. Research to reduce the carbon footprint of graphite anodes through improved processes or the use of biomass as feedstock is making progress, but the major focus remains on increasing the anode energy density. To enhance performance, there is a trend towards increasing silicon content in graphite, and a long-term effort aimed at replacing graphite altogether – but, as yet, there are almost no commercial anodes on the market that are not based on graphite. In 2024, nearly 30% of anodes for EV batteries included some silicon, typically around 5% by mass. There are two

[21] Cathode and anode can be more accurately referred to as positive and negative electrodes, respectively.

main avenues of research into alternatives to graphite that promise higher specific energies and energy densities.

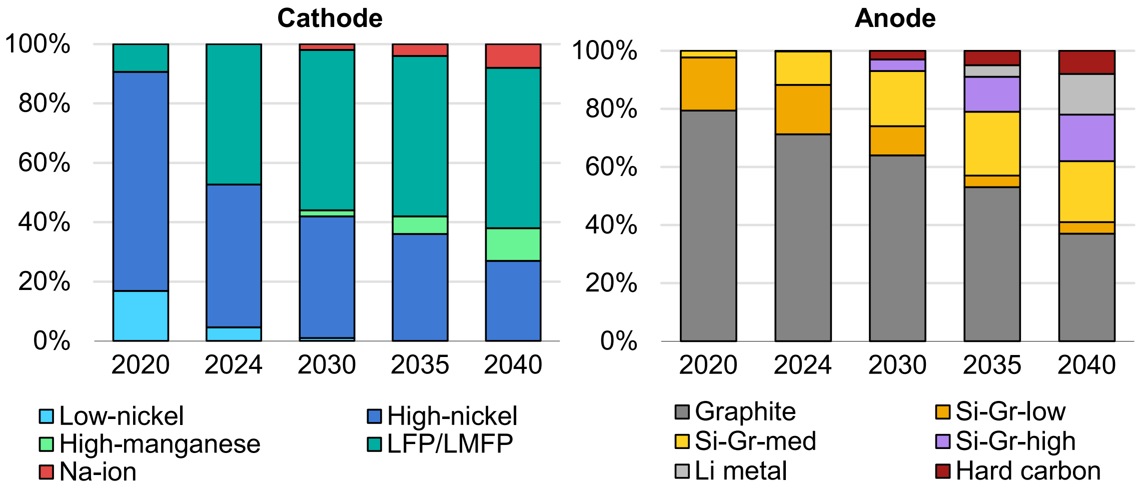
The first approach is the use of more silicon in anodes, which could eventually lead to all-silicon anodes, one of the most promising options for solid-state batteries. Silicon is an abundant material that can potentially be supplied in an environmentally benign way, and batteries based on silicon anodes can have higher energy densities than those using graphite. However, as an anode material, it suffers from problems of low electrical conductivity and volume expansion (i.e. the anode particles swell during charging), which can affect safety and battery lifetime. To address these issues, researchers – including at start-ups – are exploring a range of techniques, including physical encapsulation of the active anode material; silicon nanostructures; coating silicon particles with polymers, inorganic lithium or other compounds; adding some lithium into the anode before charging to compensate for lithium losses (pre-lithiation); and adding binders that help the anode-electrolyte interaction adapt to volume changes during charging and discharging. In 2024, US-based Amprius Technologies presented cells using silicon nanowires and reaching an energy density of 370 Wh/kg (over 30% higher than state-of-the-art NMC batteries using graphite anodes) while enabling fast charging, announcing that production will start in 2025.

Lithium metal is another anode material being investigated and it is already used in some commercial products. French company Blue Solutions markets a semi-solid-state battery with a lithium anode that requires the battery to be heated during use , and plans to build a EUR 2 billion factory in France by 2030. However, further research is needed on lithium metal anode safety and durability, which are both harmed by a chemical branching of the anode that is known as dendrite formation, among other challenges. Along with achieving higher energy densities, avoiding dendrite formation is a major impetus for solid-state batteries, though this has yet to be realised.

For non-lithium-ion batteries, an additional avenue of research is "hard carbon" anodes. With the recent development of effective sodium-ion batteries, hard carbon has emerged as the anode of reference, because graphite is not suited to use with sodium ions. Rather than needing to be mined, hard carbon can be made from resources including fossil fuels or biomass, such as sewage sludge. However, hard carbon might require considerable improvements to enable the higher energy densities for sodium-ion batteries that will likely be needed to compete with incumbent lithium-ion technologies.

The IEA base case foresees a greater diversification of anode materials from 2030 onwards, with high-silicon anodes taking a market share of almost 5% in 2030 and all-lithium anodes holding a similar share by 2035. In 2040 in the IEA base case, graphite-only anodes represent less than 40% of the market, down from over 70% today.

Electric car battery cathode and anode chemistry sales share, base case, 2020-2040



Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; Na-ion = sodium-ion; Si-Gr = silicon-doped graphite. Cathode and anode chemistry sales share is based on the electric car battery capacity. Low-nickel includes: NMC333 and NMC532 (NMC = lithium nickel manganese cobalt oxide). High-nickel includes: NMC622, NMC721, NMC811, NCA, NMCA, LNO (NCA = lithium nickel cobalt aluminium oxide; NMCA = lithium nickel manganese cobalt aluminium oxide; LNO = lithium nickel oxide). High-manganese includes lithium nickel manganese oxide and lithium manganese rich NMC (LMR-NMC). Si-Gr-low refers to 5% silicon content, Si-Gr-med = 5-50% and Si-Gr-high > 50%.
Source: IEA (2024), Recycling of Critical Minerals.

Cathodes

There are several active directions of cathode chemistry innovation. These include refinements to NMC and LFP, as well as a considerable amount of research into methods of improving battery performance while reducing the use of cobalt and nickel or eliminating lithium.

Since the advent of the modern EV market, cathode chemistries have been changed more as a result of innovation than other battery constituents. The NMC cathode family has been the dominant cathode chemistry for EV batteries for over a decade, and innovation over this period has increased energy density by using more nickel and less cobalt and manganese. Despite these improvements, simultaneous innovation in LFP cathodes has led to the Chinese batteries that contain them becoming around 30% cheaper than their NMC equivalents, while offering longer lifetimes and typically increased safety due to higher thermal stability, although this is not always the case. With improvements to LFP energy density to a level that is sufficient for most EVs, more automakers are turning towards LFP batteries. As a result, the global market share of NMC has dropped below 50%. Given that many non-Chinese producers had invested heavily in NMC, they face a crucial strategic dilemma about whether to compete in LFP value chains or to innovate for next-generation batteries instead. While some investments have been made to increase LFP production outside China, including in the United States, Korea and Europe, undercutting Chinese imports will be challenging without policy support for diversification and further innovation –

especially if China's proposed export ban on LFP technologies is enacted. In 2024, several Korean companies partnered on research to produce LFP cathodes domestically and reduce their cost, and LG Chem presented a precursor-free process for LFP cathode production. Developments in lithium manganese iron phosphate (LMFP) batteries offer a potential means of reaching even higher LFP energy densities, though Chinese companies currently lead in this area.

The emergence of sodium-ion batteries as a commercial proposition has been broadly welcomed since 2022 due to their potential to diversify away from lithium-based cathodes. However, as demonstrated in 2023 and 2024, when lithium prices dropped dramatically, sodium-ion batteries are still not competitive with LFP batteries when lithium prices are low. Achieving higher energy densities for sodium-ion batteries is a core strategy for narrowing this price disadvantage and enabling it to be a useful insurance against high lithium prices, as one can be readily substituted for the other. However, such a strategy faces the challenge of maintaining two supply chains, and is likely to only be feasible for very large manufacturers that can invest in the capabilities to produce both types of battery.

Avenues of EV battery cathode innovation that could improve battery mineral supply diversity

Cathode class	Potential benefits	Limitations	TRL (2020)	TRL (2024)	Recent progress
LMFP as an incremental improvement to LFP (for lithium-ion batteries)	Increase energy density, thermal and chemical stability, while retaining LFP cost advantages and low critical minerals requirements.	Requires lithium.	7	8 9	In 2024 in China, six commercial EV models were equipped with LFMP. Integrals Power, a UK firm, announced higher energy density achievable with LFMP cathodes.
Sodium metal oxide or poly-anion systems (for sodium-ion batteries)	Contain few critical minerals but can still include some, such as nickel.	Sodium-ion batteries are typically uncompetitive when lithium prices are low because of their lower energy density.	4	8	The first EVs using sodium-ion batteries hit the market in late 2023 in China. In 2024, a 200 MWh stationary storage facility was connected to the Chinese grid. In 2024, Chinese automaker BYD began building its first sodium-ion battery plant in China and launched its first sodium-ion battery for grid storage. The French start-up TIAMAT is scaling up production of poly-anion sodium-ion batteries.

Cathode class	Potential benefits	Limitations	TRL (2020)	TRL (2024)	Recent progress
Prussian white cathodes (for sodium-ion batteries)	Contain no critical or expensive minerals.	It is challenging to cost-effectively remove the interstitial water in the crystal structure and it is prone to produce gases during operation, both of which reduce safety.	4	8	In 2024, Chinese battery maker CATL released its Freevoy battery, which can combine sodium-ion and lithium-ion batteries in the same pack. CATL first-generation sodium-ion batteries used Prussian white cathodes. CATL also announced its second generation sodium-ion battery to start production in 2025, but its chemistry has not been disclosed. In 2023, Altris, a Swedish start-up, unveiled a Prussian white cathode material.
Lithium- and manganese-rich variations of NMC (for lithium-ion batteries)	Reduce cobalt and nickel content while increasing energy density.	Requires lithium (more than today's NMC batteries), nickel, and cobalt.	6	7	In 2023, Umicore, a Belgian company, stated it was targeting commercial production of manganese-rich NMC cathodes for EVs by 2026.
Sulphur (for lithium-sulphur batteries)	Increased specific energy that could find a market for e.g. aviation, shipping and trucks; does not require nickel, cobalt, manganese or graphite.	Requires lithium anodes. Has a complex cathode structure. Poor cathode utilisation, risks of cathode dissolution, and high volume of electrolyte generally cause relatively low durability and energy density.	4	5 6	In 2024, Lyten, a US start-up that sells lithium-sulphur batteries for non-EV uses, announced plans for the world's first gigafactory. In 2024, Stellantis and Zeta partnered to commercialise batteries by 2030. In 2024, Chinese and German researchers reported better lab-scale durability for a solid-state design.
Prussian blue (for potassium-ion batteries)	Contain no critical or expensive minerals.	Similar to Prussian white.	3	4	In 2024, US start-up Group1 produced a potassium-ion cell in cylindrical form for the first time.
Multi-valent (for batteries based on aluminium, calcium, magnesium or zinc)	Potential for high energy densities using abundant elements.	Technologies still in their infancy. Slow charge and discharge with multivalent ions.	3	3	Pre-insertion of metal ions is being studied to enhance the ion diffusion kinetics and improve the material stability during the insertion/de-insertion of the multivalent ions.

TRL= technology readiness level.

Electrolytes

Electrolytes for today's EV batteries contain a lithium salt in an organic solvent, typically a mixture of ethylene and dimethyl carbonate. Aside from lithium, liquid electrolytes do not contain critical minerals and – with the possible exception of solid electrolytes – their lithium requirements are typically negligible compared to those of cathodes.

Research to improve lithium-ion electrolytes focuses on making them solid (or semi-solid) to enable batteries that are more energy-dense, potentially offering faster charging and enhanced safety. However, this tends to increase lithium demand compared to existing lithium-ion batteries, often uses high energy cathodes like NMC, and might require materials whose supply chains are less established (or not yet established at all). Several approaches to less-flammable electrolytes are being pursued, including ceramic, sulphide, or other categories of solid electrolytes, polymer electrolytes (which are already used in portable electronics), ionic liquids and heavily fluorinated systems. For EV applications, these alternatives are all at TRL 6 or below, with the exception of polymer electrolytes, which have been tested and deployed in EVs and buses in France and Canada. Solid-state sodium-ion and lithium-sulphur batteries are less developed, but have recently received attention from researchers, particularly in the United States and Europe.

In 2024, solid-state batteries moved closer to commercial reality with announcements and investments from Samsung SDI, Toyota, Nio, Honda, Quantum Scape, BASQUEVOLT, and Factorial, among others, and the creation of a government-led Chinese battery alliance including large producers such as CATL, BYD, SAIC, and Geely to accelerate solid-state battery development. However, the potential advantages still need to be demonstrated for battery cells and packs manufactured at scale and tested under controlled, realistic and standardised conditions, meaning the TRLs of solid-state batteries are limited to 6. This could change rapidly though, with companies like Toyota and BYD planning production by 2027-2028 with limited initial volumes. Researchers are focusing on reducing the pressure needed for effective operation in a battery pack, integration of cheaper or higher-energy-density cathodes and higher-energy-density anodes (like lithium metal and silicon) and developing manufacturing techniques suited for solid-state. Some of these techniques, such as dry coating, can also be used for lithium-ion batteries, and are expected to become cheaper thanks to economies of scale. While solid-state battery costs are expected to remain relatively high this decade, more competitive prices could be achieved in the 2030s.

Reuse

Reusing EV batteries can reduce demand for critical mineral inputs from virgin raw materials and has long been promoted in the context of sustainable future EV markets. Reuse of battery-containing vehicles is important in this context, as the second-hand market will help ensure that batteries are used for as long as possible before arriving at their “end-of-life”.[22] As end-of-life batteries typically

[22] The latest state-of-the-art lithium-ion batteries have 10-year warranties for nearly 1 million kilometres, after which they can be guaranteed at 85% of their original capacity for another 5 years.

have lower capacities compared to new batteries, they may not be appropriate for new EVs but can be used for mobility applications with less stringent requirements, such as two- and three-wheelers or home storage, delaying battery recycling. In addition, disassembly, grading, testing, quality control and insurance against future failures can make reuse uneconomic compared with the continually decreasing costs of new batteries.

Recent innovation developments for EV battery reuse include the commercialisation of home electricity storage products containing batteries salvaged from EVs, such as by Irish start-up Range Therapy and US start-up Smartville. Renault has announced it will offer remanufactured electric motors and second-life batteries to its customers. In 2024, China established a state-owned enterprise for resources recycling and reuse, with a registered capital equivalent to USD 1.4 billion. The company is also dedicated to collection, pretreatment and material recovery of battery manufacturing scrap and end-of-life batteries.

Technology innovation could help battery reuse reach higher levels. Despite the EV battery market being much larger than the stationary storage battery market, even in a faster transition scenario in line with countries' announced climate pledges, only around 10% of stationary storage is met by end-of-life EV batteries by 2050. Improved technology in several areas could improve this outlook, which could be especially helpful in emerging markets and developing economies, where affordable energy storage can be key to ensuring energy access. Focus areas for technology improvement include:

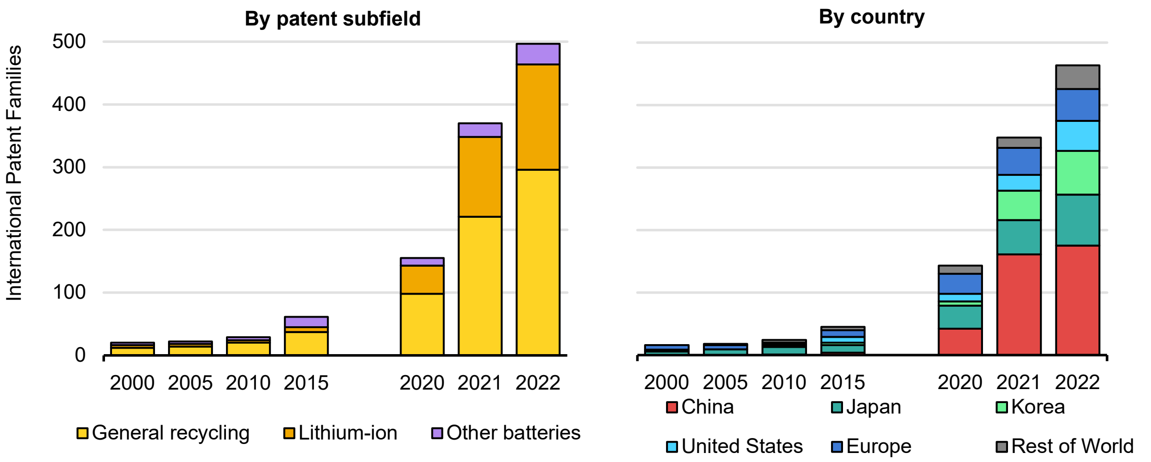
- Standardisation of battery design to reduce risks associated with battery pack disassembly.
- Diagnostic tests to accurately identify the level of degradation in an end-of-life battery.
- Efficient and safe replacement or disconnection of underperforming cells within a battery module or pack.
- Cost-effective repackaging of the battery cells for the new application.
- Tracing technologies to make transparent the origin, content and history of batteries are needed to support the implementation of a global battery passport, and reduce the risks and costs of battery reuse.
- Robust battery tracking is key for EV batteries, as they may end their first life far from where they were originally sold.
- Improved charging protocols and charging practices to enhance battery performance at the end of their first life.

Recycling

Recycling is crucial to the security and sustainability of critical minerals supply. While recycling does not eliminate the need for investment in mining, it creates a valuable secondary supply source that reduces reliance on new mines and enhances supply security for countries importing minerals, if recycling is performed and the recovered materials are used domestically. In a scenario in which countries fulfil their announced climate pledges, we find that recycling reduces global lithium and nickel demand by about 25% and cobalt demand by about 40% by 2050. In the same scenario, the market value of recycled energy transition minerals grows fivefold, reaching USD 200 billion by 2050. Moreover, scaling up recycling mitigates the environmental and social impacts related to mining and refining while preventing waste from end-use technologies ending up in landfills. While the by-products of recycling, such as sodium sulphate, must be handled properly, recycling remains environmentally beneficial on balance. Recycled battery metals such as nickel, cobalt and lithium can incur 80% less greenhouse gas emissions than primary materials produced from mining and refining.

However, future recycling of EV batteries cannot be taken for granted, even though the market value of recycled battery metals experienced nearly 11-fold growth between 2015 and 2023, with more than half of this growth occurring between 2020 and 2023. Regulatory barriers to transporting end-of-life batteries or recycling feedstock persist, while current recycling technologies face challenges due to the complexity and diversity of battery products. Highly reactive elements like lithium and mixed feedstock containing multiple battery chemistries can further hinder recovery rates.

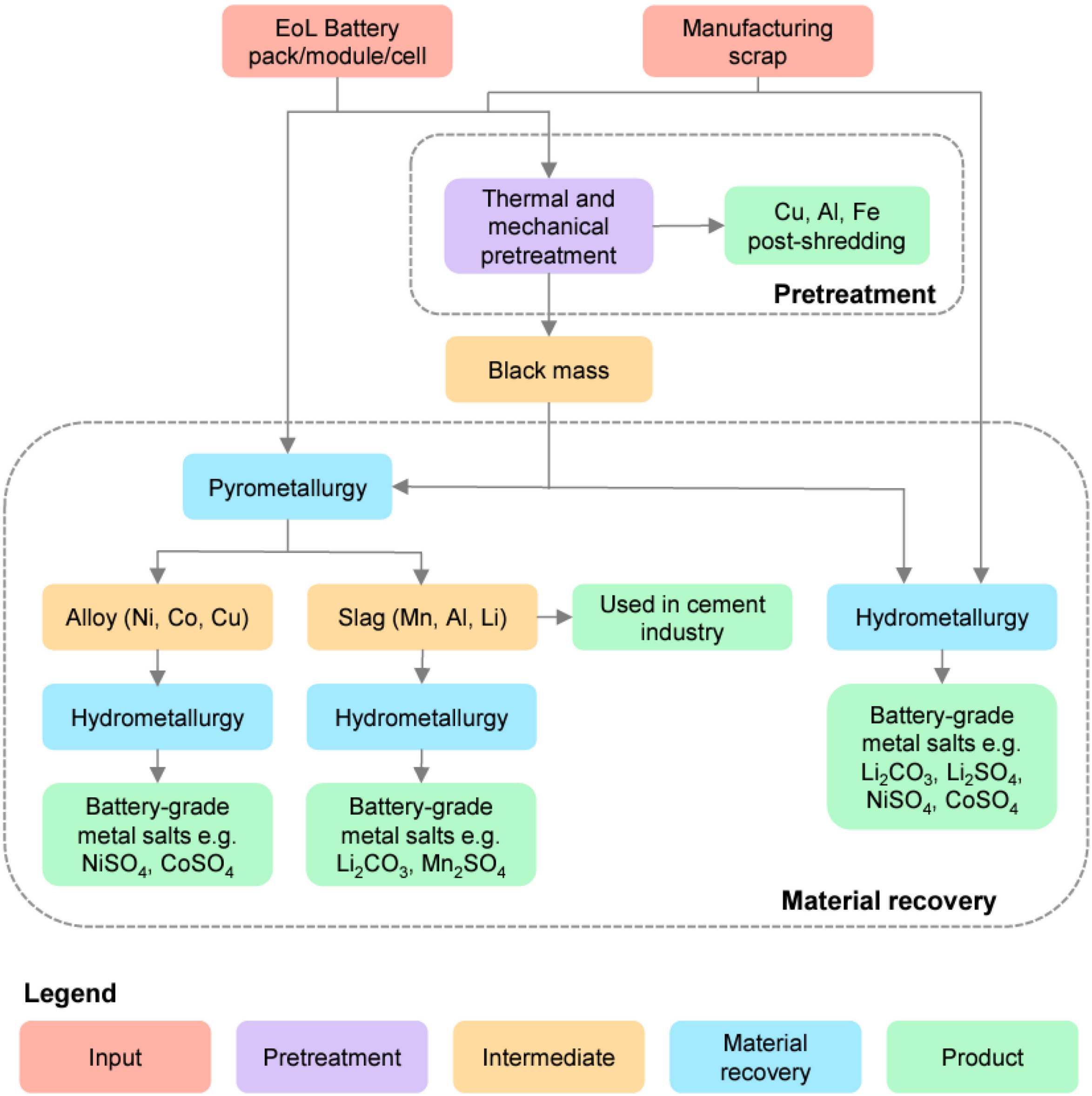
Patents for battery recycling technologies by sub-field and country, 2000-2022



Notes: Other batteries include lead acid, nickel metal hydride, nickel cadmium and disposable batteries. Each international patent family represents a unique invention and includes patent applications targeting at least two counties. Some international patent families may be labelled in more than one sub-field.
Source: IEA (2024), Recycling of Critical Minerals, based on data from the European Patent Office.

Technological improvements are needed at all steps of the recycling process to help it to compete with mined minerals, and/or to help meet regulatory requirements. At the same time, insufficient supply of end-of-life batteries this decade, low critical mineral prices and competition for feedstock among first-mover recyclers and re-users, could lead to market consolidation. The lack of end-of-life batteries could be further exacerbated if EV batteries continue to outlast initial lifespan expectations. While it is encouraging that lithium-ion battery recycling patents grew at an average compound annual rate of about 50% from 2017 to 2022, government support may be needed for these innovators to survive financially and refine their processes in the period until end-of-life battery supplies start flowing more strongly in the 2030s.

Battery recycling processes and pathways



Notes: EoL = end-of-life; Cu = copper; Al = aluminium; Fe = iron; Ni = nickel; Co = cobalt; Mn = manganese; Li = lithium; $NiSO_4$ = nickel sulphate; $CoSO_4$ = cobalt sulphate; Li_2CO_3 = lithium carbonate; Mn_2SO_4 = manganese sulphate; Li_2SO_4 = lithium sulphate. Manufacturing scrap refers to discarded battery cells, modules, or electrode materials generated during the production process.
Source: IEA (2024), Recycling of Critical Minerals.

EV battery recycling today uses manufacturing scrap, not end-of-life batteries

To date, most battery recycling facilities have been strategically located next to battery manufacturing facilities. This is because manufacturing scrap is expected to account for two-thirds of recyclable material in 2030, and even more than this in the interim. For example, US start-up Redwood Materials has a partnership with the Tesla-Panasonic gigafactory in Nevada, recycling its manufacturing scrap, while the world's largest battery recycler, Brunp, is a subsidy of CATL, the world's largest battery manufacturer. Due to China's large share of battery manufacturing, over 80% of pretreatment and material recovery capacity for recycling battery materials is in China.

Manufacturing scrap is expected to be overtaken as the main available input in the 2030s and end-of-life EV and storage batteries could represent over 90% of feedstock by 2050. Developing and refining efficient collection and recycling processes for end-of-life batteries – which are significantly more challenging to recycle than manufacturing scraps – will be crucial this decade.

Pretreatment

Pretreatment refers to batteries being discharged, dismantled and mechanically or thermally treated to condition them in order to ease material and metal recovery, typically in the form of black mass. It is the least complex and costly stage of battery recycling. It typically involves both thermal processes that remove components such as the organic carbonates in the electrolyte, and mechanical processes that shred, sieve, sift and float battery parts to separate components based on properties such as size, density, magnetism, shape and conductivity. The resulting "black mass" is a powder containing the cathode and anode materials and thus the valuable battery minerals. Innovation in pretreatment is focused on advanced sorting, novel chemical and physical processes, and quality control.

Redwood Materials – a US-based start-up that has partnerships to supply minerals with BMW, Ford, General Motors, Panasonic, Toyota and Ultimum Cells – raised over USD 1 billion in equity and received a conditional loan of up to USD 2 billion commitment from the US government in 2023 to expand its battery recycling operations. Its thermal calcination process is powered by the residual energy in end-of-life batteries, which should minimise the combustion of graphite and plastics and avoid slag formation. It also has proprietary hydrometallurgy processes operating at a scale of 15-20 GWh per year, and a plant in construction. In 2023, Redwood Materials acquired Redux, a German firm with 10 000 tonnes per year of thermal and mechanical pretreatment capacity.

Material recovery

Material recovery refers to the recovery of battery materials and metals after the pretreatment step, typically from black mass. It is the more technical and complex recycling stage. Of the two main approaches to material recovery, pyrometallurgy is more flexible and involves smelting in a high-temperature oven, recovering part of the metals as alloys and the remainder as oxides (slag). The high temperatures burn the graphite in the anodes, which becomes impossible to recover. The other main approach, hydrometallurgy, involves chemical leaching and purification processes to precipitate out individual battery-grade materials, or intermediate products for further chemical processing. While hydrometallurgy alone can recover cobalt, lithium and nickel from black mass, this requires more pretreatment, which leads to losses. Therefore, it has become common to apply hydrometallurgy to the outputs of pyrometallurgy, and recent technical developments have enabled higher lithium recovery rates from the combined process. Around 5% of global battery lithium recycling capacity is now in combined pyrometallurgy and hydrometallurgy plants, compared with more than 90% in plants for hydrometallurgy alone.

Hydrometallurgy is the focus of technological innovation today, as existing designs of pyrometallurgy plants are generally flexible enough to cope with a wide range of black mass inputs. In contrast, hydrometallurgy processes are usually designed for specific inputs and grades of outputs, which increases the risk that they will be affected by changes in the battery market. For example, the growing share of LFP batteries, which represented almost half of the global electric car market in 2024, up from just over 10% in 2019, could have negatively impacted investment in hydrometallurgy plants targeting nickel-rich chemistries such as NMC.

Among the promising recent technical developments in hydrometallurgy are processes for recovering graphite and iron phosphate. Graphite recycling is economically challenging due to the low price of graphite and the technical difficulties of its recovery, making it difficult for recycled graphite to compete with virgin material. However, it is eligible for the 45X US tax credit, which improves investment prospects in the United States. Export controls introduced by China in December 2023, coupled with the geographical concentration of its supply chain, have also increased incentives to develop graphite recycling. In 2024, US start-up Ascend Elements and Mexican chemicals company Orbia's subsidiary Koura was awarded a USD 125 million grant from the US government to build a US facility to commercialise a process that it says can recover 99.9% pure graphite. In Germany, in 2024, researchers demonstrated a potentially low-cost method of graphite recycling with no loss of battery performance.

For iron phosphate, in 2023 the Chinese company Botree reported having developed a recycling process that can recover up to 90-95% of lithium and 85-95% of iron phosphate, but the economics of LFP battery recycling are expected to remain challenging and largely dependent on the lithium spot price, which may limit investments. To support battery minerals research, including an integrated approach to pyrometallurgical and hydrometallurgical recovery, Umicore, a Belgian metals company with a recycling plant in its home country, agreed a EUR 350 million loan for R&D from the European Investment Bank (EIB) in 2024. However, this takes place against the backdrop of a scale-back of the firm's battery metal activities as the region's EV deployment has underperformed expectations in the past year.

Electrochemical extraction, which can avoid the direct use of fossil fuels to provide the heat for pyrometallurgical processing, is a relative newcomer to the technology landscape. Start-up Nth Cycle raised USD 44 million in December 2023 to expand its first small-scale commercial facility for producing nickel from scrap and other waste streams, as well as R&D towards other metal products. In addition, Mangrove Lithium, a Canadian start-up, secured USD 35 million for a lithium refining facility.

Direct recycling

Direct recycling is an emerging recycling process that can potentially achieve very high recovery rates while decreasing energy intensity. Rather than break down the cathode material into its constituent metals, it retains the material crystal structure and regenerates the cathode material by replacing lost lithium. It could be well-suited to cathodes such as LFP, which contain fewer valuable minerals. However, it must be tailored to each cathode chemistry and recovered cathodes can be repurposed only for the same battery chemistries, though methods are being developed for remaking them in similar but newer chemistries. For any new plant with an expected multi-decade lifetime, this raises significant risks of stranded investments if a cathode's chemistry is outdated by the time it reaches end-of-life. Other technical challenges include direct recycling's requirement for complete separation of anode and cathode materials, which is difficult for end-of-life batteries.[23] China-headquartered Farasis Energy, Swiss start-up Kyburz and Brunp (a subsidiary of CATL) are all working in this area. Direct recycling is currently at the large prototype stage (TRL 5). In 2024, Toyota signed an agreement to support Argonne National Laboratory in the United States to further test its process.

Accessing alternative mineral resources

Efforts are underway around the world to find cost-competitive new sources of battery minerals in locations where they are not currently mined in order to diversify supply chains. Innovation typically focuses on diffuse resources that could become economically viable as the market expands or if manufacturers are

[23] For manufacturing scraps, cathodes and anodes are often already separated.

incentivised to source raw materials more locally. The resources include brines (which contain lithium, among other salts), mining and processing waste, and the seabed.

Lithium from brine

As much as two-thirds of global lithium demand in 2023 was met from mines in just two countries – Australia and Chile. In Australia and China (which accounted for almost 20% of mined lithium in 2023), lithium is mined from hard-rock ores, whose resources are highly geographically concentrated. In the so-called Lithium Triangle encompassing northwest Argentina, southwest Bolivia and northern Chile, evaporation and chemical precipitation are used to extract lithium from continental brine deposits. However, this process requires concentrated resources and high solar irradiation, takes 10-36 months, and causes the loss of high volumes of water. Many more countries have less concentrated lithium brine sources that cannot be accessed with evaporitic technology. Economically sound technologies to exploit these more dilute lithium resources are being explored.

Direct lithium extraction (DLE) technologies for recovering lithium from dilute brines – such as geothermal and oilfield – include thermal and electrochemical processes. These methods significantly reduce water consumption and speed up month-long lithium recovery to a few days or less compared with evaporation through solar irradiation, though they are typically over three times more energy-intensive. [24] However, their energy intensity is only about 20% compared to hard-rock lithium ore mining. Geothermal brines are currently of particular interest given for geothermal energy projects to expand around the world, many of which have not previously hosted geothermal extraction. Several large oil and gas companies are investing in DLE in the hope that its similarities with oil extraction and refining processes offer a competitive advantage. There is fierce competition between different approaches that have the potential to ultimately achieve the lowest costs for battery-grade products. Many new partnerships and projects were announced in 2024 that could take new DLE technologies to the next TRL in 2025. The Chinese government's proposed export ban on direct lithium extraction technologies may also incentivise innovation elsewhere.

[24] DLE demonstration projects for lithium from near-surface deposits are already in operation in Chile and Argentina in the hope they might replace evaporation methods.

Avenues of direct lithium extraction innovation

Technology type	Potential benefits	Limitations	TRL (2020)	TRL (2024)	Recent progress
Adsorption	Uses relatively few chemicals; adaptable; low waste; low energy inputs; low environmental impact; and over 90% yield.	Needs high salt concentrations; high water demand (potentially incurring water recycling costs). High upfront costs. Can cause brine contamination. Needs temperatures >40 °C.	5 6	8 9	• In early 2025, the US government made a conditional commitment to loan up to USD 1.36 billion to Energy Source Minerals to build at a geothermal location the first commercial-scale US project (up to 3.3 kilotonnes per year [kt/yr] lithium). Energy Source Minerals' subsidiary ILiAD, the technology provider for the project, became part-owned by two major extractive industries firms, SLB and Rio Tinto, in 2024. • CalEnergy Resources, a subsidiary of Berkshire Hathaway Energy, and Occidental partnered in 2024 to construct a 17 kt/yr lithium US geothermal brine demonstration project by the 2030s for a technology owned by Occidental Petroleum. • Controlled Thermal Resources began construction of an integrated lithium-geothermal power project that could supply 4 kt/yr lithium by 2027 and 13kt/yr lithium more by 2030. This follows successful operation in 2023 of a pilot project at the same location in the United States. • Vulcan Energy, a German-Australian start-up, piloted lithium production from geothermal brine in Germany in 2024 and secured the equivalent of up to USD 550 million in debt from the EIB and USD 130 million from the Australian government in export credit to scale up operations there to 4 kt/yr lithium by 2027 and 4 kt/yr more by 2030. • LevertonHELM and EnBW successfully produced highly pure lithium carbonate from their German geothermal brine pilot project in 2024 and agreed to proceed to 0.1 kt/yr lithium by 2028. • Weardale Lithium, a UK start-up, successfully produced lithium carbonate at its UK pilot project in 2024 and plans to proceed to 2 kt/yr lithium by 2028. • Eramet's Ageli pilot project in France has been under development since 2023 and the partners aim for 2 kt/yr lithium by 2030.
Ion exchange resins, ion sieves and sorbents	Lower upfront costs; high precision (especially promising for low concentrations); low energy and water demand.	High OPEX. Requires large quantities of acids and bases, creating safety risks. Requires post-treatment and purification.	4 5	7 8	• Lilac Solutions, a US start-up, reported 84% lithium recovery from low-grade brines and raised USD 145 million in equity (USD 315 million since 2016) to develop a 0.6 kt/yr lithium above-surface brine project in the United States by 2026. • E3 Lithium*, a Canadian start-up, finalised a pilot project with their proprietary ion exchange technology. • Summit Nanotech, a Canadian start-up, filed a new patent for its technique in 2024 and signed an agreement with a Chilean mining company to begin deployment on above-surface brines in Chile.

Technology type	Potential benefits	Limitations	TRL (2020)	TRL (2024)	Recent progress
Solvent or liquid–liquid extraction	Up to 90% recovery achievable; adaptable; low OPEX; limited demand post-treatment.	High CAPEX; requires large volumes of chemicals; high waste production. Requires intensive pretreatment (if high levels of calcium and magnesium are present).	3 4	7	• Adionics, an Argentinian start-up, proved the effectiveness of its process at pilot scale on above-surface brines in 2024. • Syensqo – formerly part of Belgian chemical company Solvay – recently developed a solvent for lithium extraction from brines that could also be applied to lithium-containing waste streams.
Electromembrane and permselective membrane processes	Enables modular design; high recovery rate; streamlined and continuous operation; high efficiency; high purity output; low energy demand; relatively environmentally benign.	High CAPEX and OPEX (for membrane regeneration). Requires pretreatment. Membrane degradation may contaminate reservoirs and reduce geothermal energy output.	2 3	4 5	• Lithium Infinity, a Saudi start-up, successfully extracted lithium from oilfield brine in 2024 and is planning a pilot project with Saudi Aramco. • Watercycle Technologies, a UK start-up, raised USD 5.6 million to scale up its pilot facility for lithium extraction from waste and aquifer water sources. • In 2024, US researchers reported a redox-couple electrodialysis method that could result in more efficient lithium extraction from oilfield brine.
Nanofiltration membranes	Enables modular design. Increased water and lithium recovery; reduced energy consumption. Allows extraction from lower-grade brines and claystone.	Costly – requires high upfront investment and OPEX; lower chemical resistance leading to faster degradation; high energy consumption; requires pretreatment.	2 3	4 5	• In July 2023, US chemical company DuPont announced the commercial launch of nanofiltration membrane elements for lithium brine purification. It won a 2024 Sustainable Technology and ESG Award for its low water and energy demand.
Selective precipitation (aluminate, phosphate, carbonate)	High purity outputs; adaptability. Can be combined with other DLE processes.	Requires post-processing (to remove co- precipitates). High OPEX (costly reagents). Generates wastes that need treating.	3 4	4 5	• A recent study demonstrated fast lithium precipitation and the production of high-quality lithium carbonate from Uyuni (Bolivia) brine.

* E3 Lithium secured the equivalent of USD 3.7 million in 2024 from the Government of Alberta for its demonstration project, utilising a third-party technology, and plans to continue developing its proprietary technology.

Notes: Lithium capacity is expressed in kt/yr of lithium content and not lithium carbonate equivalent (LCE) or lithium hydroxide monohydrate (LHM) equivalent. Conversion rates used are 0.188 for LCE and 0.165 for LHM.

To help provide like-for-like comparisons of several of the competing technologies in order to inform decision-making, ENAMI, a Chilean state-owned institution that supports small-scale miners, announced in December 2024 that it would invite eight companies to test their technologies on its brines.[25] The results could help provide meaningful evaluations of the technology characteristics for that class of brine. In the United States, the government granted USD 225 million to a DLE project at an Arkansas underground reservoir in early 2025.

Reclamation from mining and waste

Mining and processing wastes are largely untapped non-concentrated sources of minerals. Recovering minerals from mine waste, also known as tailings reprocessing, is a growing area of interest. As ore grades decline, larger amounts of waste are generated during mining, increasing the economic and environmental cost of managing tailings. Advances in processing technologies and degrading ore quality means that old tailings might soon have comparable mineral concentration compared to current mines, effectively attracting investors to harvest those resources. Companies like UK-based Altilium, Australian Cleanteq and US-based Phoenix, among others, have technologies that lead to lower mine or processing wastes compared to older technologies or recovery of minerals stored in existing tailings.

Phytomining (or agromining) involves cultivating selected plants known as hyperaccumulators on metal-rich soils to extract high value metals, including cobalt and nickel. Hyperaccumulator plants can naturally take up concentrations of metals that are up to 100 times greater than other plants growing in the same soils. Nickel phytomining has been demonstrated in the field in Albania and Malaysia, and in 2024 the US Department of Energy announced USD 10 million to support phytomining projects and start-ups. In Europe, Genomines, a French start-up working on extracting nickel from plants, is working on genetically enhanced plants that can accumulate a larger amount of minerals. For cobalt, the candidate species is ubiquitous in Zambia and can accumulate around 1% of its mass in cobalt, making it an option for removing soil contamination from mining. For these two metals, phytomining has been estimated to be economically feasible given the limited opportunity costs for the use of these soils, but its economics are heavily dependent on mineral prices.

[25] Selected companies (among 30 applicants) are CADL-Lanshen (China), ERAMET (France), Lilac Solutions (United States), Rio Tinto (Australia), SLB (United States), Summit Nanotech (Canada) and WaterCycle Technologies (United Kingdom).

Advanced mineral exploration and extraction

Technology innovation can also improve mineral exploration and extraction. Combinations of more data, artificial intelligence (AI) models, automation and new processes have the potential to hasten access to new mineral resources while reducing the environmental impact of mines.

Kobold Metals, a US start-up, and GeologicalAI, a Canadian firm, combine geological data, satellite imagery and AI to make minerals exploration more accurate and faster, potentially reducing total costs. If the pace at which new mineral resources are identified and brought to market can be reduced, it will help address the issue of long time lags to bring online copper and lithium mines to meet arising supply gaps.

Technologies are also being developed by the mining industry to increase productivity while addressing environmental impacts. More automation and digitalisation – including digital twins to identify potential disruptions before they arise (see Chapter 8) – autonomous vehicles, drones for monitoring, and remote or automated drilling and blasting are all being tested and developed. Changes to rock comminution could also help lower energy intensity, for example by using emerging techniques such as pulsing power to crush and grind ores. There are also potential synergies with carbon dioxide removal if mine tailings can be used to react with CO_2 to create permanent stores (see Chapter 9).

Seabeds

Progress is also being made at the technological frontiers of mining hard-to-access concentrated resources, but these tend to be associated with broader concerns about resource ownership and uncertain environmental impacts.

An active innovation area is deep sea mining, notably with a view to accessing the Pacific Ocean's Clarion Clipperton Zone. Companies are developing technologies that are at around TRL 3 to remove nodules of minerals (manganese, nickel, cobalt, copper) from the seabed. However, regulations are not expected to be finalised by the International Seabed Authority until the end of 2025 or later and environmental impacts remain hard to monitor. Some countries have proposed a moratorium, and Norway, which solicited proposals for projects in its territorial waters early in 2024, later suspended its plans. Furthermore, significant gaps remain in the scientific knowledge of environmental impacts of seabed mining, and total recoverable volumes in the medium term are unknown. Whether the firms can secure the necessary permissions and cost levels to compete with land mining and recycling by the end of the next decade is highly uncertain.

Nonetheless, some investors are taking the risk of supporting technical developments, and the US government committed USD 2 million for a feasibility study in 2025. One area of research is in machines that can excavate sea-floor nodules and monitor the associated disturbance, while attached to a boat by kilometres of cable. The first pilot projects for this type of system to have taken place since the 1970s were conducted privately by a Canadian and Belgian firm in international waters in the early 2020s. Some extracted minerals have since been processed. Another approach is to use untethered autonomous battery-operated excavators, a research version of which was demonstrated in Canada in 2024. The Chinese government sponsored trials in the Pacific Ocean in 2024 and more trials are planned for 2025.

Knowledge gaps to be filled

The research and commercialisation results presented in this chapter demonstrate the breadth of effort that is being directed to different ways of using technology to diversify battery mineral supply chains. These are not all in competition – recycling, reuse and new sources of lithium will be compatible with a range of emerging battery chemistries – but some are in tension. For example, battery reuse delays recycling and, if nickel- and cobalt-free batteries come to dominate the EV market, battery recycling might become less profitable. Investors and governments must think carefully about whether to support a wide range of possible outcomes or align efforts around a narrower vision. While recent history with LFP demonstrates the challenge of predicting the precise composition of the battery market 5 years in advance, this knowledge gap should not prevent decision makers being as well-informed as possible about global innovation trends when they allocate funds to R&D, demonstration and manufacturing projects.

Research to date has uncovered several challenges that will require innovation efforts if the technologies are to make a positive impact on the market in the next decade. Given the scale of the battery industry and its expected growth, many incremental challenges will be resolved through market-based competition. Some of the examples listed below may need dedicated support to overcome bigger hurdles, and to realise the benefits of supply chain resilience, which can be undervalued by the market:

- Reducing materials intensity (especially of nickel for oxide cathodes) and increasing energy density is the priority for developing **sodium-ion batteries** as a source of flexibility that can partially replace lithium-ion batteries or outcompete them in certain applications, including cheaper batteries for cold climates. Recent developments in China suggest that Chinese companies currently have a growing advantage in this area, and their manufacturing experience could be applied in new supply chains that are not (or less) reliant on scarce raw materials.
- To help guide expectations for future market developments, it is essential that promising **solid-state batteries** are advanced through the demonstration stages to gain manufacturing experience. Only through production of solid-state battery

packs, even if they are initially expensive, will this family of technologies be able to resolve questions about cost, performance and safety.

- Support for **lithium-sulphur batteries**, which may be appropriate for weight-sensitive applications like aviation while minimising scarce mineral inputs, remains important, but the technology still requires significant improvements and demonstration at scale.
- If the market conditions are favourable, we should expect widespread ingenuity in how batteries might be **reused**, though improvements to the price and performance of new batteries may continue to squeeze the markets in which reuse can compete. Battery reuse is also currently hindered by a lack of international standards for how to guarantee the performance and safety of repackaged batteries for new purposes and facilitate their international trade. Technological advances in international battery tracing and tracking, software and packaging will help address these concerns.
- There is a need to continue the testing and optimisation of novel battery **recycling** processes, including direct recycling and electrochemical extraction. In the period before end-of-life batteries are widely available, the objective should be the development of robust tracking and collection systems and a suite of competitive recycling technologies that are as flexible as possible with respect to different chemistries and that allow for the optimal handling of byproducts.
- The flurry of project announcements in the past 2 years for **direct lithium extraction** from geothermal and oilfield brines has the potential to reveal the most promising techniques for different types of lithium resource. However, there are still risks that good projects will not secure the finance to proceed, raising the importance of co-ordinated public and private support. In addition, data that can be compared on a standardised basis should be collected to transparently inform future customers and efficiently prioritise R&D.

Priorities for reaching the next innovation stages

If successful, the technologies reviewed in this chapter will lead to EV battery supply chains that rely far less on the mining of individual critical minerals, especially those whose supplies are geographically concentrated, and which are more resilient to disruption and price spikes. Policy makers can co-operate internationally to ensure that knowledge gaps are addressed, and they can provide targeted financial support for innovation priorities and skills training. In addition to the traditional use of R&D grants, this area of technology may be appropriate for incentivising innovators through prizes and other financial instruments. At the same time, governments must also consider more strategic tasks related to the scale-up of the battery sector, strengthening demand and boosting production competitiveness to accelerate the market impact of innovations.

Support battery production scale-up. Achieving long-term competitiveness in battery supply chains is a complex task involving a wide range of actors. The difficulties encountered by Northvolt in Europe in 2024 as it worked to scale up production are instructive: strict quality control, high manufacturing speed, automation and access to a skilled workforce are indispensable to achieve high production yields, and just as important as innovation in battery design or chemistry.

For the commercialisation of a more radical technology in a cut-throat market, these elements may be even more important, as challenges faced at the industrial scale are not the same as at the laboratory scale and may require devoted innovations. Governments wishing to establish domestic production and innovation must act strategically, for example by creating hubs of expertise, easing companies' growth and production scale-up, and encouraging a co-ordinated innovation strategy across the supply chain in line with current and future market trends. One aspect of such a strategy is ensuring that the gap between academia and the corporate sector is closed through support for networks for experts and collaborative projects.

Promote recycling and embrace a long-term vision. For recycling, regulations can enhance market-based incentives to invest, but it is important that they reflect real-world expectations for battery supply and demand. The looming gap between the number of innovators seeking to scale up this decade and the availability of end-of-life batteries means that many of them face a wide "valley of death". The overcapacity that already exists in China means that recycling plants would have an average utilisation rate of only 20% today, even if all the available material in China were collected. In advanced economies, the potential lack of sufficient off-takers for recycled minerals – such as companies producing cathode active materials – raises further challenges around effective supply chain diversification and investment in facilities that can use these recycled outputs, or partnerships with companies overseas that can, with Korea being an option in this regard.

Patient capital and government funding are therefore likely to be needed to ensure that a variety of promising approaches can be tested and refined, including novel pricing schemes and business models.[26] Competing battery recycling innovators will all need some access to the limited flows of waste material in the coming years. Financial support appears even more important in the context of the recent volatility of mineral prices and the more challenging economics of recycling LFP compared with NMC; LFP batteries have only one valuable metal to recover and sell, which is lithium. Similar dynamics apply to sodium-ion and lithium-sulphur batteries, which contain few or no minerals with high commercial value.

[26] Toll-based recycling and revenue-sharing could offer recyclers better economic stability and encourage long-term investments.

Nonetheless, recycling challenges should not overshadow the need for more affordable EVs. High shares of LFP recycling can be scaled up with supportive regulation, as has been achieved for lead-acid vehicle batteries that have low-value components.

Ensure regulatory clarity and foster international co-operation. Clear, long-term regulations are needed, including export rules for used batteries and EVs, as well as the implementation and enforcement of enhanced producer responsibility requirements. Regulations governing international trade in part-recycled content, such as black mass, and end-of-life batteries, will also need to be clarified. Furthermore, recycling, like most industrial processes, is not free from environmental and social impacts: Poorly managed battery recycling may result in pollution from waste residues, water contaminants and harmful emissions. In some countries, the waste collection stage has involved child labour or unsafe practices that can only be effectively addressed by tackling poverty, including more formalisation and professionalisation of the workforce.

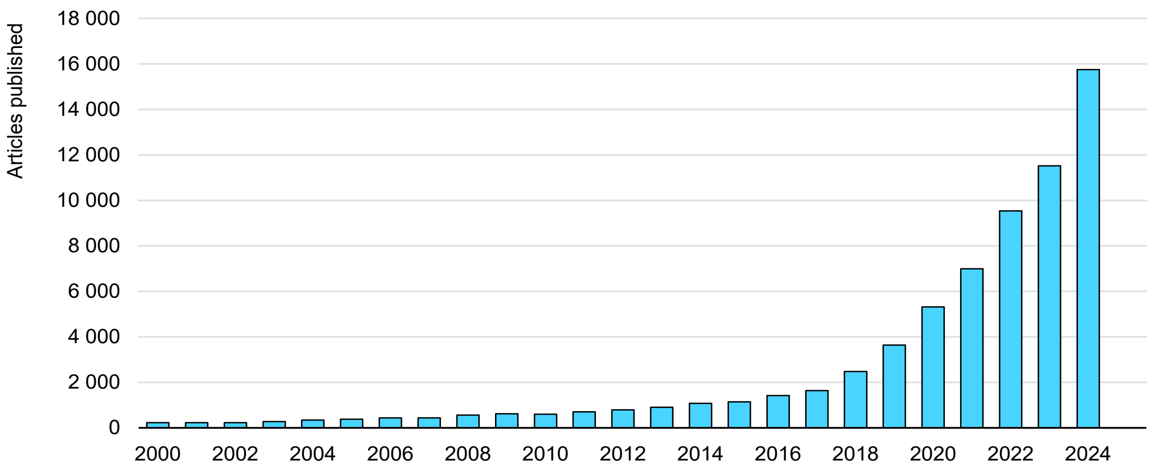
Voluntary standards are emerging, but gaps in social and governance aspects remain and efforts to further strengthen recycling standards are needed. Traceability mechanisms can allow stakeholders to verify that materials are sourced and recycled according to best practices, and also allow consumers to favour producers and recyclers with higher environmental and social performance.

Align available EV models with consumer needs. A further area where governments can play a crucial role is in incentivising EV makers to produce vehicles that are no bigger than consumers need for their purposes. This so-called "right-sizing" can enable significant reductions of total battery demand, and therefore of mineral needs, of up to 2 TWh of battery demand to 2030, which is nearly equivalent to the batteries in the global EV fleet in 2023. Fast-charging batteries and infrastructure are additional developments that can be expected to help reduce the need for large battery packs, lowering resource demands.

8. Focus: Artificial intelligence for energy technology innovation

Like the steam engine and electricity, artificial intelligence (AI) is a general-purpose technology that could profoundly transform the global economy and the world's energy system. Though key uncertainties remain, it stands to have major impacts, including through its capacity to enhance and accelerate the process of energy technology innovation. AI can expand the capabilities and creativity of scientists in generating and testing new ideas, something that is already being demonstrated in a range of research papers and projects.[27] The volume of research articles on the use of AI to address energy technology challenges has expanded dramatically in recent years. A recent study of the impact of using AI tools in an industrial research setting showed a 39% increase in patenting by the company in under 2 years.

Published research articles at the interface of energy and artificial intelligence, 2000-2024



Note: Based on a keyword search of scientific journal articles.
Source: Elsevier (2025), Scopus abstract and citation database.

[27] This chapter employs a broad definition of AI to include a range of different tools, whether generative, agentic, predictive or physical. Put simply, a predictive machine-learning AI model uses complex corelations to identify an optimal solution in a dataset, a generative AI model (like a large language model) can design new solutions, an agentic AI model is similar but more adaptable to new information, and a physical AI model can control hardware and respond to a changing environment. While there is a large difference between the machine learning models of 10 years ago and the generative AI models of 2025 in terms of data needs, electricity intensity and precision, the chapter does not judge whether researchers are applying the most appropriate tools to each problem. However, there is a discernible trend towards more use of generative and agentic approaches that have higher computing requirements, and it can be assumed that much future research will involve combinations of the different types of AI models.

Finding a higher-performing material for a task, or one that does not contain certain undesirable inputs, has typically relied on human ingenuity and knowledge of how different compounds behave. However, the number of possible options is often vast. AI techniques are already excellent at solving problems by optimising for well-understood relationships across large and well-structured data sets.

While work on the use of AI for scientific discovery has been underway for more than a decade, several striking developments in 2024 raised awareness of its potential use for energy technologies. For example, the reported identification of a new solid battery electrolyte by researchers from US multinational Microsoft and a US government laboratory. It now appears clear that most research work will incorporate the use of machine learning, large language models or other AI techniques soon – possibly by the end of this decade. In some areas, such as the search for new chemical compounds that can dramatically outperform existing battery components or lower the energy needs for synthetic fuel catalysis, the promise is large. While the pace of battery cost declines has been fast in recent years, it may slow down as battery prices approach material costs – however, if AI can help discover and scale up innovative, cheaper designs then new phases of cost reduction might be unlocked. AI could be a means of realising in practice the extrapolation in theoretical models of recent cost trends into the future. Time will tell if AI keeps current learning rate projections on track or becomes a more disruptive force that makes today's projections look very conservative.

Not all energy technology challenges can be equally addressed by AI, which will be able to generate more complete or more easily implemented solutions in some technology areas and have more limited impact in others. This chapter explores the ways in which AI might help accelerate energy innovation, the status of the techniques and some emerging priorities for government action. A first step would be a more comprehensive inventory of promising technology areas and available AI tools (models, databases).

There are two related topics that this chapter does not cover. Innovation that seeks to reduce the energy intensity of all forms of AI, and innovation that seeks to apply AI to broader energy challenges, such as electricity grid optimisation, are covered in other IEA work. Notably, these topics are taken up in the Special Report on Energy & AI. They are both important areas that are becoming established elements of the overall energy technology innovation landscape.

The ways in which AI can enhance innovation

The technology readiness level (TRL) ladder is a means of grouping the stages of innovation for a given product. The ways in which AI can boost these stages varies and can be thought of in three main segments:

- TRL 1 to TRL 3: identifying a potential design, structure or concept that is predicted to outperform known alternatives.
- TRL 4 to TRL 6: testing a prototype, first in isolation and then as part of an integrated system.
- TRL 7 to TRL 9 and beyond: attracting customers and resources for commercial scale-up.

To the extent of our knowledge, most applications of AI to energy innovation so far have focused on the first of these – the identification of promising potential design or concepts. These types of problems are often well-suited to AI because they involve searching a well-defined set of options for a solution to a specific scientific problem, such as finding a more efficient catalyst. Outside the energy sector, AI has already been used to elicit unforeseen scientific discoveries related to pharmaceuticals and protein design. The ideal candidate problems for this type of use of AI are considered to have a common set of features:[28]

- a broad search space
- a defined objective for model training
- substantial data or simulation capabilities
- straightforward methods for synthesis and testing under standard conditions
- relative ineffectiveness of non-AI tools for predicting optimal solutions within the search space.

In general, therefore, AI is most likely to accelerate progress towards meeting challenges relating to identifying better chemical compounds, materials and biochemical entities such as proteins and enzymes. In this sense, it is building on work since the 1960s to apply computation and high-throughput methods to materials R&D. In the near term, this will be most effective in areas where well-structured and well-populated databases of candidate entities already exist, complete with their physical characteristics and behavioural properties. In such cases, practitioners consider the reduction in screening time to be 99% or more.[29]

There are also use cases that relate to the optimisation of the form of a component, such as a turbine blade, by simulating a wider range of possible solutions than would be possible without AI.

However, identifying a new material for an energy application via a computer-based method is less than half of the innovation task. Synthesising and

[28] Drawing on a hypothesis outlined by Demis Hassabis, as well as other sources.
[29] However, this rough figure may not provide a like-for-like comparison given that, on the one hand, humans are more selective about screening more viable candidates and, on the other hand, humans would be highly unlikely to identify certain less-obvious candidates that may be found to have unexpectedly high potential.

prototyping, followed by commercialisation, mass manufacturing and widespread market uptake, can take years or even decades. Effort is also being directed towards the use of AI-related tools to compress these timetables, which in some cases can be more important than the discovery phase for shrinking the overall time from new design to market uptake. As AI becomes an increasingly indispensable part of the research process for energy technologies, innovators will also benefit from developments in adjacent areas, including improved robotics and automation.

For prototyping and testing, so-called self-driving labs are being developed for energy applications and new projects in this area were unveiled in 2024. If accurate testing of predicted designs can be undertaken very rapidly, then research strategies can shift to include more sequential testing, which can allow findings to be integrated into new designs more efficiently than with parallel testing. For reducing the risks, and therefore the costs, associated with large-scale first-of-a-kind demonstrations of new designs in heavy industry and other sectors, AI-enriched tools such as digital twins hold promise. Risks associated with attracting customers and scaling up production might be further reduced by using AI analysis of data generated by new products to raise their value to consumers, as well as use of AI for better operational decision-making by software controlling the new technology. As with all technology innovation, the commercialisation stage will be smoother and more likely to succeed if the new product has high complementarity with existing infrastructure, markets and consumer preferences.

There is a possibility that the use of AI might lead to types of innovation that do not follow the stages outlined in this section. For example, rather than being used to identify a higher-performing component for a known type of battery, a set of algorithms might be able to optimise for the general problem of electrochemical energy storage and propose an entirely new type of device that had not previously been considered. This is certainly exciting territory, but it needs to be demonstrated in practice.

As of early 2025, few energy technology products have been commercialised that contain components proposed by AI methods. However, several established companies and start-ups are working to bring their AI-assisted designs for batteries to market in the near term. Besides batteries, the status is less developed but maturing quickly. The following section outlines the main technology applications that have been reported and where they stand today.

Technology landscape

Battery electrodes and electrolytes

Despite impressive improvements in lithium-ion battery performance and cost in the past decade, there is still significant room for further innovation that can help batteries to penetrate further into markets for road vehicles, aviation, home energy storage and utility-scale energy storage. If innovation continues at its current rate, future battery designs are expected to store more energy per unit mass and unit volume, and be more durable, less-flammable and less reliant on scarce raw materials. Some researchers are using AI to improve the key components – such as electrodes and electrolytes – of mature types of lithium-ion batteries, while others are using AI to find components that could raise the TRL levels of novel battery types like solid-state, sodium-ion or multivalent electric vehicle (EV) batteries. However, because battery production relies on complex supply chains and must adhere to stringent quality standards, entirely new materials and components are unlikely to have impacts in the medium term without equivalent improvements to the commercialisation process.

Selected developments for the use of AI to enhance battery cathode and electrolyte innovation

Reported advance	Reporting year	Country	TRL*	Next step
Wildcat Discovery Technologies, a start-up focusing on faster development of novel anodes and cathodes, signed offtake agreements with US lithium iron phosphate (**LFP) battery** makers and received its 100th patent. It has raised around USD 145 million since 2006.	2024	United States	9	Construction of a new plant.
Mitra Chem, a start-up seeking to manufacture cathodes designed with AI, began commercial production of **LFP cathodes** and production of samples of novel lithium manganese iron phosphate (LMFP) cathodes. It also received a USD 125 million grant from the US government and has raised USD 80 million in equity since 2021.	2024	United States	9	Continue to synthesise and test thousands of cathode designs monthly to add to its catalogue.
Chemix, a start-up that claims higher prediction accuracy for battery materials identification, raised USD 20 million in equity to expand its platform for screening and autonomously synthesising electrolytes for more energy-dense **LFP batteries**.	2024	United States	5	Move into manufacturing its designs to fulfil an agreement to supply 2 GWh of EV batteries.

Reported advance	Reporting year	Country	TRL*	Next step
PhaseTree, a start-up working to commercialise its approach to predicting material behaviour, was founded following academic work on lithium-ion oxyfluoride cathodes, and raised over USD 3 million to expand its scope.	2025	Denmark	3	Apply the technique to other similar energy materials challenges for customers.
Scientists synthesised for the first time a candidate for a stable electrolyte for a **solid-state lithium-ion battery** that had been proposed by an AI-driven method. Aionics, a start-up that aims to design electrolytes based on this approach, partnered with the battery manufacturing subsidiary of Porsche and raised nearly USD 5 million in equity.	2024	United States	3	Further tests of lithium thioborates and application of the method to other compounds.
Researchers from a US government laboratory and Microsoft assessed 32.6 million possible new **solid-state electrolytes** for lithium-based batteries and found 18 new ones with the right characteristics, including the novel option of lithium and sodium dual-ion batteries.	2024	United States	2	Consider more complex materials. Predict and rank the synthesis path and integrate screening with direct generation of materials for testing.
Scientists screened 45 million potential molecules and found nearly 4 600 promising candidates for an **organic cathode** for alkali-ion batteries.	2023	Sweden	2	Synthesis and testing.
Scientists screened 40 000 materials and identified a promising candidate for a non-lithium-containing cathode that could work in a future **lithium-anode battery**.	2023	United States	2	Repeating the process with a larger set of potential materials.
Polaron, a start-up working to commercialise its method of **lithium-ion cathode** optimisation, was founded following publication of code for inferring device-level performance by fusing molecule-level images.	2023	United Kingdom	2	Apply the technique to other similar problems for customers.
Chinese researchers reported the use of machine learning to discover possible lithium salts that may make possible their hypothesised approach to cheaper **non-lithium cathodes** and battery rejuvenation. Using a training dataset of 10 076 candidates from literature, they identified 240 candidates and selected 1 for synthesis and characterisation.	2025	China	2	Test the candidate salt and external lithium supply approach in a battery cell.

* TRL levels in the tables in this chapter refer to the technologies within each class that have been designed or developed with AI input.
Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate.

Catalysts for electrolysis and fuel synthesis

Catalysts are substances that can reduce the energy inputs required for an industrial process, for example by binding to a reactant in a way that holds it in place so that there is a stronger guarantee of reaching a desired outcome. Inventing new catalysts is typically an incremental process whereby experts modify a compound that is known to work well in a similar situation. Through trial and error, researchers at BASF spent over 3 years systematically screening more than 2 500 catalysts to improve ammonia production. Inventing whole new classes of catalysts occurs more rarely. However, the ability of AI to screen large numbers of possible options very quickly could lead to more regular leaps in progress in the efficiency of key low-emissions energy processes such as the production of hydrogen from water, the synthesis of liquid fuels from hydrogen and carbon dioxide, and the production of chemicals from non-fossil resources.

A conversion efficiency improvement of one percentage point will not translate into the same impact on overall energy costs for each reaction, as they vary widely in terms of capital requirements, energy and feedstock costs, and the costs of adjacent processing steps. This means that catalyst improvements could be most impactful for reactions with high energy and feedstock costs, and few additional steps to arrive at a finished product, such as synthetic fuel production. Parallel innovations to reduce the price of energy and other inputs, such as sustainable CO_2 sources, will also be critically important for commercial success.

Selected developments for the use of AI to enhance catalyst innovation

Reported advance	Reporting year	Country	TRL	Next step
Dunia Innovations, a start-up working to commercialise a method of **catalyst design**, raised USD 11.5 million and engaged customers in Asia.	2024	Germany	3	Expand the automated screening and experimental validation beyond the identification of anion exchange membrane electrolysis catalysts.
Researchers reported a method to explore the catalytic performance of 623 dual metal site catalysts combining of 27 metal elements and found four candidates that are predicted to outperform platinum in **electrolysers and fuel cells**.	2024	China	2	Synthesise the catalysts and test the predictions.
The DECODE project was launched with EU funding to develop the concept of connecting laboratories via the data cloud to collaborate on AI-driven energy materials discovery, with an initial focus on **catalysts for water electrolysis**.	2023	European Union	1	Develop protocols and procedures for data exchange.

Reported advance	Reporting year	Country	TRL	Next step
Meta, the University of Toronto and VSParticle published experimental results on over 570 materials to enable faster AI-based identification of **catalysts for hydrogen electrolysis and synthesis of fuels** from hydrogen and CO_2.	2024	United States, Canada and the Netherlands	1	Continue to make datasets available as part of the Open Catalyst Project.
Calicat, a start-up developing **hydrogen electrolysis catalysts** with AI based on US government-funded research, reported that its iridium-free catalysts showed durability around 18 times longer with 10 times more current density than other equivalent catalysts. The company raised USD 3 million in 2024, taking its total equity raised to USD 21 million since 2021.	2023	United States	3	Deliver effective materials as part of partnerships with De Nora and Tokyo Gas.

Enzymes and proteins for bioenergy

Some of the most promising applications of AI techniques to scientific prediction and discovery to date have been in biotechnology. The AlphaFold programme is perhaps the most well-known example of this. It has been the world’s leading source of protein structure prediction since 2018, contributing to medical understanding and drug discovery. Energy-related applications, however, have lagged despite a few research teams looking at enzymes for biofuel fermentation and polymer disassembly. One such technique is referred to as directed evolution: it mimics the process of natural selection by subjecting a gene to iterative mutagenesis (i.e. artificially creating a library of “mutant” variants), isolating those with a desired function and using these as a template for the next round. While directed evolution has been used in laboratories for several decades, machine learning enables the initial library to be orders of magnitude larger, and allows the candidates predicted to have the right properties to be autonomously screened with high-throughput techniques.

Research in this area is at an early stage and is not uniformly distributed. One study found that funding and studies in the field of biofuels and machine learning were relatively geographically concentrated, with significant shares for India, the United States, China, Malaysia, Nigeria and Brazil.

Selected developments for the use of AI to enhance energy-related biotechnology innovation

Reported advance	Reporting year	Country	TRL	Next step
Samsara Eco, a start-up that uses AI to identify enzymes that can depolymerise complex plastics, raised USD 65 million in 2024.	2024	Australia	6	Work towards a commercial plant to recycle nylon fabric and avoid virgin fossil fuel inputs.
Scientists used machine learning and CRISPR-Cas9 to select and test 31 yeast strains from a pool of 216 candidates and achieved a 7% increase in bioethanol production.	2023	Thailand and China	2	-
Researchers confirmed that a machine learning method could predict the expected bioethanol yield from untested lignocellulosic bioenergy resources and thereby avoid wasted effort testing unattractive feedstocks.	2021	Poland	2	-
Scientists used machine learning to improve the processing conditions for converting lignocellulosic feedstocks to bioethanol.	2022	India	2	Evaluate the method for other processes such as acid hydrolysis and alkali hydrolysis.
Researchers confirmed that a machine learning method could predict the expected biodiesel yield from untested oilseed resources and thereby avoid wasted effort testing unattractive feedstocks.	2021	India and Finland	2	-

Materials for solid-state CO_2 capture and hydrogen storage

Inorganic materials such as metal organic frameworks (MOF) can trap molecules like carbon dioxide and hydrogen inside if they are engineered to have the right properties. These properties include the size of the holes in the material and its responsiveness to changes in external conditions that cause the release of the MOF contents on demand. Finding the ideal material for a given task is complex and requires predicting interactions among a range of different parameters, something that AI is becoming much better at.

Selected developments for the use of AI to enhance energy-related MOF innovation

Reported advance	Reporting year	Country	TRL	Next step
Orbital Materials, a start-up that has developed a generative AI tool for designing materials for CO_2 capture, raised USD 16 million in equity and an undisclosed sum from NVIDIA.	2024	United States	3	Commercialise CO_2 capture materials and further develop solutions for synthetic fuels production.
Researchers employed a generative AI large language model in the prediction of MOF properties for CO_2 capture, potentially for direct air capture of CO_2.	2024	Korea	2	Further optimisation of "ChatMOF".
Scientists generated 120 000 candidate MOF designs for CO_2 capture and screened them using a generative AI technique, leading to validation of 102 satisfactory (but not breakthrough) options in a total of 11 hours.	2024	United States	2	Online learning methods to generate even higher-performing MOFs.
Researchers used machine learning to identify a new class of MOFs that immobilise palladium as a catalyst and can trap CO_2 to make its conversion to methanol more efficient.	2024	Norway	2	Continue to characterise and test the novel material.

Compounds for perovskite solar PV

Perovskite solar cells show promise as a third-generation PV technology, with high efficiencies achieved in the laboratory and new commercial techniques for manufacturing them in tandem with silicon PV cells emerging in recent years. In 2024, the record for pure perovskite cell efficiency was raised to 26.7%, while the record for a perovskite tandem cell – which expands the spectrum of light that can be absorbed – was set at 30.1%. Both records were achieved in China. For multi-crystalline silicon – the current industry standard – the record is 24.4% and commercial products are typically up to 22% efficient. Higher efficiency reduces land costs for PV installations and allows more power to be produced on small roofs.

Making perovskites competitive requires identification of new chemical combinations, structures and manufacturing processes to improve stability and costs. However, the potential combinations are vast: less than 0.01% of possible perovskite materials have been experimentally produced. Progress has been constrained by manual selection of candidate chemistries and labour-intensive synthesis and testing. A recent review found 284 relevant publications on the use of machine learning to enhance perovskite innovation across the past 5 years, mostly focused on material composition and performance analysis. One important avenue of research is the avoidance of lead, which is toxic, and hazardous solvents. The review concluded that there has been limited application of machine learning to improve perovskite manufacturing to date and the use of generative AI methods are underexplored in this area. However, while machine learning can estimate properties of unexplored perovskites, its reliability remains constrained by the low availability of high-quality, real-world data. In addition, interest in using machine learning to improve the manufacturing of perovskite PV cells is increasing and deserves more attention.

Selected developments for the use of AI to enhance perovskite solar PV innovation

Reported advance	Reporting year	Country	TRL	Next step
Scientists developed a method of screening 180 038 compounds, with which they identified 4 lead-free organic-inorganic double-perovskites with appropriate PV characteristics and enhanced thermal stability compared with other known candidates.	2021	China and Japan	2	Improving the reliability of the data library and refining the model.
Researchers in the United Kingdom reported a process involving machine learning, assisted material screening, robotic synthesis, and high-throughput characterisation. With a training set of 1 758 perovskites and 227 non-perovskites, 5 000 candidates were proposed and several validated with experiments after human-AI down-selection.	2024	United Kingdom	2	Improve the AI's ability to generate workable syntheses. Reduce the human involvement in selection.
Scientists integrated predictive modelling with autonomous synthesis and optimised across multiple parameters to identify 24 molecules that outperform prior benchmarks and 1 with a predicted efficiency of over 26%.	2024	Germany, China and Korea	2	Refine the approach into a seamless, closed-loop process.
Researchers created an open-access database for perovskite solar cell analysis with AI based on the FAIR data principles ("findable, accessible, interoperable and reusable"). It was initially populated with data for 42 000 devices.	2021	International	1	Expand the dataset and ensure data-sharing by practitioners.

Materials for magnetocaloric cooling and heating

Magnetocaloric cooling is another area of energy innovation that relies on predicting the properties of new combinations of chemicals from a very large set of options. The technology, based on a concept discovered a century ago, uses electricity to make a magnetic field that changes the temperature of a solid material and thereby cool a gas or liquid. The advantages include around 25% higher efficiency compared with mainstream mechanical processes based on vapour compression and avoidance of the leakage risk associated with using greenhouse gases as working fluids. Solid-state cooling is viewed by many as the future of cooling, and magnetocaloric cooling is the highest-TRL solid-state approach. However, it only reached the prototype stage in 2021 for applications such as air conditioning and industrial refrigeration and is currently at TRL 6. There is a need to improve the heat transfer materials, reduce production costs (with cheaper components and economies of scale) and expand into lower temperature areas such as cryogenic liquefaction of hydrogen. An additional and emerging area of application is the reversal of the system for electricity generation.

Selected developments for the use of AI to enhance magnetocaloric cooling and heat innovation

Reported advance	Reporting year	Country	TRL	Next step
Researchers used a large language model (GPT 3.5) to auto-generate 6 000 candidate materials by screening published research outputs, and identified 11 promising materials for industrial cooling with diverse and novel compositions.	2024	United States	2	Use simulation data to retrain the model and iterate.
Scientists showed how different machine learning methods perform in the prediction of novel near-room temperature magnetocaloric materials using data on 511 samples from the scientific literature. Seven candidates were synthesised to validate the predictions.	2024	China	2	-
Researchers identified 8 rare-earth-free magnetocaloric materials for hydrogen liquefaction by applying machine learning to a dataset of 603 samples. Eight were manually tested and one showed the best performance so far of a material in this class.	2022	Japan	2	Alloy design and hysteresis engineering to increase the magnetic entropy and reversible adiabatic temperature changes.
A new EU-funded project was launched to explore machine learning-based prediction of magnetocaloric material function in the area of converting low-grade waste heat to electricity. Magnoric, a start-up that successfully operated the first prototype of a magnetocaloric cooling system, is a partner.	2024	Pan-European	1	Develop the datasets and models.

Rare-earth-free permanent magnets

Permanent magnets are important components of modern energy technologies, including wind turbines. However, they currently require rare earth metal inputs that are not evenly distributed internationally. The supply chains for rare earth magnet elements – neodymium, praseodymium, dysprosium and terbium – are concentrated, with the top three mining countries (China, Australia and Myanmar) accounting for 85% of supply. The prices of these elements have been volatile in recent years and demand for them is set to grow by nearly 45% by 2030, by which time China alone is expected to represent 77% of refining. Making cost-competitive permanent magnets without rare earth elements has so far eluded researchers, but AI has recently indicated some new avenues for exploration.

Selected developments for the use of AI for rare-earth-free permanent magnet innovation

Reported advance	Reporting year	Country	TRL	Next step
Microsoft and Chinese Academy of Science researchers reported a generative "diffusion" model for proposing stable inorganic materials fine-tuned to desirable properties. They claim to double the share of proposed candidates that are stable, unique and novel, while improving prediction of physical properties. This was applied to a training set of 607 683 stable structures with up to 20 atoms to identify 95 possible magnets with low supply chain concentration.	2025	United States, the Netherlands, China	2	Improvement of the MatterGen model, including by expanding the training data, in order to improve the quality of the outputs. Application to other materials problems.

Self-driving labs for testing predictions

If AI assistance helps scientists to simultaneously screen all the materials for which data is available or can be predicted, and to do so more than 100 times faster, testing the identified candidates will soon become a major bottleneck. A potential solution could be found in so-called self-driving labs, which can be automated to synthesise materials rapidly – by designing appropriate recipes based on a material's elemental composition – to test them, and use the results iteratively to suggest new candidates. From 2018 to 2020, in response to a need identified by Mission Innovation, the first self-driving lab for energy materials was built in Canada, initially for thin-film solar PV design and now applied to CO_2 electrolysis. More examples of self-driving labs for energy technologies have been created in the past 2 years.

Improving and replicating these closed-loop laboratory models is likely to be crucial to accelerating energy innovation with AI. They must also be made cheaper; contemporary self-driving labs are very complex and expensive – potentially reaching tens of millions of dollars – because they require custom robotics and access to high-performance computing. Expanding their suitability to a wider range of materials is also important – for example, they are currently hard to design for catalysis of synthetic fuels due to the high-temperatures and multiple reaction phases. Furthermore, moving from synthesising and testing material samples to producing integrated devices significantly increases the hardware requirements. This can be addressed to some extent by connecting different laboratories with complementary capabilities, a process that requires laborious alignment of protocols, data formats and methodologies. Such cost barriers reduce the availability of self-driving labs to many researchers around the world.

Selected developments for the use of AI to synthesise and test energy materials

Reported advance	Reporting year	Country	TRL	Next step
Miru Smart Technologies, a start-up commercialising electrochromic windows that reduce heating and cooling needs, raised USD 20 million. Earlier funding from the Canadian government helped Miru to build a self-driving lab that helped create a new colour-neutral window product.	2024	Canada	5	Test and license the windows via partnerships.
A US government laboratory began operation of a series of robots that can synthesise chemicals predicted to enable better batteries through computer calculations. In 17 days, the lab ran 355 experiments and synthesised 41 of 58 proposed solids with diverse structures, 50-100 times more samples per day than a human-run equivalent.	2023	United States	3	Reduce discrepancies between predictions and outcomes, and include microstructure and device performance factors.
Atinary, a Swiss start-up founded in 2017, and ViperLab, an EU-funded perovskite project consortium, published new work on the use of machine learning to improve synthesis of new candidates and identify functionalities that can signify materials that will be effective at large scales.	2024	Switzerland	3	Integrate the experimental and machine learning approaches into a self-driving lab for perovskite solar PV.
The 13-year USD 56 million Danish Pioneer Center for Accelerating P2X Materials Discovery is developing processes for AI-accelerated discovery of scale materials and catalysts for Power-to-X.	2023	Denmark	2	Developing selective and scalable catalysts for electrochemical reduction of CO_2 to sustainable fuels and chemicals.
The Canadian government awarded its largest ever grant to a university (equivalent to USD 140 million) to further the development of seven self-driving labs with a focus on low-emissions energy and health.	2023	Canada	3	Expand existing labs and create a new lab to assist scale-up of the outputs.

Digital twins and controls for complex projects, including for nuclear and large-scale demonstrations

For large, complex systems, a computer-based aid known as a "digital twin" can significantly reduce the costs and risks of design and scale-up. Digital twins, which are virtual representations of all the elements of a specific facility or process, have been used to optimise manufacturing for over a decade but are now being powered by AI and applied to innovation. It is a technique that can reduce the costs and risks of scaling up manufacturing of a new product, for example by analysing up to 10 billion data points produced per day by a battery gigafactory to characterise performance, detect faults and diagnose problems.[30] In sectors such as nuclear fusion, digital twins are helping design and test equipment, and they are also being used in the development of small modular nuclear fission reactor designs. This approach is expected to help provide evidence of the safety of new designs and reduce the time it takes to certify them. In addition, it could be a significant fillip for innovators of technologies with large unit sizes and a need for extensive engineering designs to demonstrate the technology at commercial scale.

However, while there is an expectation that the costs of complex engineering design can be sharply reduced by this approach – particularly for expensive, first-of-a-kind projects – many digital twins today are not yet able to take advantage of AI, partly due to limited data for model training. Existing instances of digital twins for scaling up energy innovations are already promising. For example, Shimizu, a Japanese company, reported in 2024 a digital twin system for reducing the time for designing and permitting projects in the construction sector. POSCO, a large Korean steelmaking company, announced plans in 2022 to build a virtual steel mill to cut the costs of a first-of-a-kind hydrogen-based direct reduced iron plant. ORLEN, a Polish energy utility, and Yokogawa, a Japanese engineering and digital services firm, announced in 2023 a partnership to build a virtual replica of a 70 kilotonnes per year synthetic fuels production facility to be constructed by 2030. The addition of AI approaches to such systems in due course could significantly improve their accuracy and predictive capabilities.

In recent years, AI has become an increasingly integral part of nuclear fusion research. Simulations that previously took hours now take less than one second. For many years, scientists have been working towards nuclear fusion as a large-scale source of low-emissions energy that would be almost unlimited, non-radioactive and safe. If nuclear fusion is to become a source of energy in the future, it appears certain that AI will play an important role, especially as the power of AI will increase significantly during the decades before nuclear fusion is

[30] Number of data points based on an annual utilisation factor of 85% for a 50 GWh plant with hundreds to thousands of data points per cell, a cell voltage of 4 volts, and cell capacity of 60 ampere hours (prismatic) or 3 ampere hours (cylindrical).

commercialised. Translating nuclear fusion into a commercial reality by the second half of this century still requires multiple technical advances in a variety of areas to improve the economics of nuclear fusion in comparison to nuclear fission. Materials that can withstand extreme temperatures and irradiation for more than 40 years will likely be needed. More powerful lasers will be needed, as will technologies for breeding tritium. Better diagnostics and control of confined plasma will be necessary. New materials for superconducting magnets could improve performance. At the same time, the major risks associated with building multi-billion dollar first-of-a-kind cutting-edge facilities must be managed.[31] Experts believe that many of these challenges can be significantly aided by AI.

Selected developments for the use of AI for digital twins and controls to enhance nuclear fission and fusion innovation, and complex large-scale demonstration projects

Reported advance	Reporting year	Country	TRL	Next step
Assystem, a French engineering company, and Naarea, a French start-up founded in 2020 to develop a molten salt micro fission reactor, announced a partnership to create a digital twin of the reactor design using large language models.	2024	France	2	Deploy the digital twin to finalise the design of a prototype to be built by 2028.
Proxima Fusion, a start-up that builds on work undertaken for the EU- and German-funded W7-X experimental stellarator, raised USD 30 million in equity to build surrogate models for testing new stellarator designs with AI, thereby reducing development costs. The start-up also received up to USD 19 million from the European Union in grants and equity.	2023/2024	Germany	2	Increasingly detailed engineering design.
Commonwealth Fusion Systems received several million dollars from the US government to employ high-performance computing. The start-up has raised over USD 2 billion in equity for its promise of achieving net energy gain this decade, rather than in the mid-2030s, in part by speeding up design cycles for its demonstration plant by an order of magnitude.	2022-2024	United States	2	Build the 140 MW plant.
Focused Energy announced plans to build a US R&D facility. In total, it has raised over USD 175 million in private equity and grants from the German and US governments. The start-up designs laser-based fusion and uses AI models to simulate possible future outcomes of different design decisions.	2024	Germany and United States	2	Build new beamlines to test the physics associated with laser ignition.

[31] As an example of the costs and risks of such engineering projects, ITER, a 500 MW facility designed to demonstrate the viability of nuclear fusion energy, was agreed in 2006, started construction in 2013, is expected to start operation in 2034 and energy generation is not expected to start before 2036. Since 2006, the timeline has been extended by over 10 years and the costs by around 200%.

Reported advance	Reporting year	Country	TRL	Next step
Google Deepmind, the AI division of Google, published the code it has developed for tokomak simulation, following a 2022 demonstration with Swiss scientists that control of a tokomak could be handed to an AI-run system that could respond in real time to regulate plasma conditions.	2024	Switzerland and United Kingdom	1	Expand the model to optimise more parameters and use more sophisticated simulation.
EURO Fusion, a consortium of European nuclear fusion research bodies that co-ordinates EU research funding, allocated almost USD 3 million to 15 new research projects using AI to analyse the consortium's large dataset and develop methods of controlling fusion reactions.	2024	European Union	1	The projects will run for 2 years.
Researchers generated unexpected laser illumination profiles by coding an AI approach to optimise across various parameters.	2024	France	1	Further refine the code and underlying data.
NVIDIA, Stanford University and Caltech built a digital twin of a CO_2 storage basin using a nested Fourier neural operator, speeding up flow prediction nearly 700 000 times compared to existing methods and reducing the costs of predicting CO_2 storage behaviour for small and medium-size entities.	2023	United States	8	Include permeability and capillary pressure hysteresis factors into the model.
nTtau Digital, a start-up, was launched to commercialise a generative AI tool that can be used by nuclear fusion developers to generate data from simulations to train models of their designs. It has been applied to tritium breeding challenges.	2022	United Kingdom	1	Launch the FusionAI service in 2025.
Researchers reported success in producing a digital twin of a nuclear fusion reactor that would allow the magnetic fusion plasma to be controlled based on real-time simulations of behaviour.	2024	Japan	2	Develop more sophisticated controls that can outperform existing methods.

Data crunching for geothermal and other subsurface resources

Geothermal projects are vulnerable to notable resource risks during project development, i.e. the risk of not finding geothermal resources with appropriate qualities (temperature, flowrate) for the planned surface application. These risks can be further exacerbated by high exploration and drilling costs, which can make it very challenging for developers of new geothermal technologies to raise capital for scale-up if they do not have large balance sheets. While several governments have put in place some type of risk mitigation facility that transfers some of this risk to the public sector, it is typically not designed to cover the higher risks associated with novel technological approaches. As a means of reducing these upfront risks, enhanced reservoir characterisation using AI is an area of active research. If the competitive and large-scale extraction of hydrogen from natural underground deposits is demonstrated, such AI techniques would have clear application in that sector too.

Selected developments for the use of AI to enhance geothermal data processing

Reported advance	Reporting year	Country	TRL	Next step
Halliburton, a US oilfield services company, launched two new products that apply machine learning to automate drilling and reduce costs.	2024	United States	9	While the technology has been tested in the oil and gas sector, it has yet to be transferred to geothermal drilling.
Fervo Energy, a US start-up developing enhanced geothermal systems, signed a partnership with Google to develop AI systems to improve Fervo's efficiency.	2021	United States	7	Build a 90 MW enhanced geothermal power plant.
The US government integrated a large language model into its open-access Geothermal Data repository, increasing the utility and discoverability of geothermal data.	2024	United States	9	-

Knowledge gaps to be filled

The research and commercialisation results presented in this chapter demonstrate the breadth and effectiveness of AI for enhancing energy technology innovation in certain areas. The use of various types of machine learning will undoubtedly become a routine feature of laboratory work for electrode, electrolyte, catalyst, MOF, perovskite and other materials discovery.

Work to date has uncovered several challenges that may not be resolved in the pursuit of current research pathways and will require dedicated efforts to overcome them. These challenges represent relevant projects for the international community to prioritise for collaboration this decade. They include:

- Address the relative lack of effort in the use of AI in some priority areas, including perovskite PV manufacture, and design of new bulk materials that avoid environmental harms, such as cements and concretes that do not generate CO_2 in their manufacture.[32]

[32] A widely cited training dataset, the Concrete Compressive Strength dataset of the UCI Machine Learning Repository, contains just 1 030 entries, for which it reports only 9 variables per entry. This contrasts strongly with other sectors like catalysis where new experimental data has continuously become available.

- Ascertain the appropriate balance between the marginal benefits of using the latest AI techniques – including large language models that are not yet widely used in this area – and the computing requirements compared with less sophisticated machine learning approaches.
- Reduce the computing requirements of materials discovery and testing using AI, including by minimising duplication of model training, and sharing experimental and simulation results widely between teams working on similar projects in adjacent fields, ensuring the interoperability of the experimental and simulation results.
- Develop flexible and open models that can integrate physics-based rules in AI algorithms and optimise across more of the characteristics that are essential for a material to be integrated into a functional product.
- Demonstrate the effectiveness of fully self-driving labs that iteratively test candidate materials and update open-access databases with the results.
- Collect expert views on the impact of AI on future learning rates for key final products, such as batteries (cost and energy density), electrolysers (cost and efficiency), CO_2 capture (capture cost), synthetic fuel production (plant cost and efficiency), solar PV (long-term cost per kWh) compared with past learning rates to inform energy system models and help prioritise research funding.

Priorities for reaching the next innovation stages

If successful, AI will not only accelerate and improve innovation outcomes but also deliver economic competitiveness. However, the full potential of AI in this area will not be realised unless governments focus on some key emerging issues upfront. If efforts are anticipated, directed and co-operative, the benefits will be shared by all countries, their innovators, investors and firms.

To drive scientific discovery towards the most impactful outcomes, there is a need to invest in searchable databases that follow common protocols and ontologies and are widely accessible, including by interconnected laboratories across international borders. The datasets used today have incomplete information about possible materials and represent a restricted subset of molecules or reactions. The development of massive, structured, specialised datasets to train AI models, such as the Materials Project and Cambridge Structural Database, is underway, but they must be further expanded if real-world scientific problems are to be solved. While the creation of "synthetic data" to train models can overcome some of the data gaps, there is no substitute for experimental data, and the fastest route to large and reliable experimental datasets is co-operation between laboratories, including at the international level. The Mission Innovation M4E platform is an example of an international initiative that could demonstrate how governments can support common protocols and jointly curated data.

Investments in skills and equipment will also be required, and policy makers can guide efforts to the most pressing technological needs. Skills gaps could be an issue in a fast-moving field, while responsive regulatory and standards frameworks will be necessary to support and accommodate new approaches to testing and commercialising products and services. If AI-powered digital twins are an additional source of evidence for regulators certifying new technologies such as nuclear reactor designs, then it is imperative that the regulators are able to accept and process the data in a timely manner. Investors too will need to be able to correctly interpret these new data sources if their potential to reduce project risk is to translate into lower financing costs.

To support commercialisation, policy makers should also consider how to make new digital tools widely available to innovators. Advances in cloud computing make it technically straightforward for researchers in emerging and developing economies to take advantage of these techniques and participate in international innovation projects. However, the cost, need for infrastructure and other barriers to accessing data can be insurmountable without direct assistance from overseas partners. At scale-up stage, small- and medium-sized enterprises in advanced and developing economies alike may struggle to access the most advanced tools and bridge the valley of death when preparing first-of-a-kind projects. Currently, AI-augmented digital twin tools are not all widely accessible to innovators in the scale-up stage.

As more research teams use AI in different fields and processing requirements rise, ready access to computing power will be critical, especially if inequality between researchers around the world is to be minimised. Governments will inevitably play a role in many countries by investing in computing facilities and facilitating access based on societal priorities. In Europe, the AI Factories initiative seeks to foster collaboration within and between AI research hubs. In the United States, nuclear researchers can apply for access to supercomputers owned by Idaho National Laboratory, but demand far outstrips capacity today. In other regions and in smaller economies, co-operation on supercomputing facilities is likely to be important. Physical high-performance computers are cheaper to use than cloud-based options, as long as they are operated at high load factors, something that governments are well-placed to invest in and ensure.

Finally, the computing and energy needs of AI for these important tasks, as well as potential risks such as those related to intellectual property, must be discussed in multilateral fora.

9. Focus: Innovation to cut the costs of carbon dioxide removal

Carbon dioxide removal (CDR) refers to a suite of technologies that are being developed to balance residual GHG emissions – for example from sectors such as industry, long-distance transport and agriculture – as well as to address historical emissions. In the past decade, a diverse set of innovative and promising technologies have been proposed to draw CO_2 from the atmosphere and permanently store it. Both technology and market progress in this area have been encouraging. In just 5 years, the corporate landscape has grown from just under 30 start-ups with a few kilotonne-scale (kt-scale) pilot projects, to over 140 start-ups, some of which are commissioning 15-40 kt-scale facilities, and utilities and oil and gas companies building 200-500 kt-scale CDR projects. In 2023, activity included a USD 1.1 billion acquisition of a CDR start-up by an oil company.

Companies are competing for a prospective market opportunity: depending on the future energy pathway, this could reach around USD 250 billion by mid-century.[33] While underground biomass storage companies advertise removal costs lower than USD 100 per tonne of CO_2 (t CO_2) per year today, scaling up the global CDR market to the gigatonne scale is likely going to rely on a portfolio of novel CDR approaches. With average reported CDR credit market prices ranging from USD 300/t CO_2 to USD 1 600/t CO_2 for more complex approaches in 2023, it is also a set of technologies that require concerted R&D and demonstration efforts ahead of being more widely deployed.

This chapter reviews progress and needs for a selection of CDR technologies with the highest chance of achieving permanent removal and with the greatest innovation needs, based on current knowledge. These include bioenergy with carbon capture and storage (BECCS), underground storage of stabilised biomass such as bio-oil injection, direct air capture (DAC)[34] including ocean-based approaches, enhanced rock weathering and ocean alkalinity enhancement. This chapter also highlights recent technical advances in the CO_2 storage space, including storage in saline aquifers, depleted fields, basalts and peridotites, and building aggregates, which underpins the scale-up of many CDR pathways. Each technology area is in need of further research and testing, and advances can

[33] Assuming demand of 1 billion tonnes per year at a credit price of USD 250 per tonne of CO_2 removed. Some models project higher demand, up to 15 Gt CO_2 per year this century.

[34] For simplicity DAC refers here to DAC plus permanent CO_2 storage (also termed DACS or DACCS), and not the capture process alone.

support developments in other fields, including the wider carbon capture, utilisation, and storage (CCUS) sector, as well as bioenergy and waste management.[35]

The case for strengthened innovation

The CDR technology landscape is complex and expanding. There are multiple ways to remove CO_2 from the atmosphere and different options for how to store it.[36] Most of the approaches are either at low technology readiness levels (TRL) or are physically limited in their capacity to scale up globally. Whether CDR is widely deployed in the coming decades depends largely on whether the costs for today's pre-commercial technologies are successful reduced through innovation. The innovation needs of the different approaches vary by technology type and whether the approach needs field testing or more incremental improvements during commercial scale-up. Improved technologies for monitoring performance will be important across all approaches and stages of maturity.

This chapter focuses on CDR approaches that are generally categorised as "novel CDR" or "technology-based solutions". They combine a range of biological, geochemical and chemical CO_2 capture processes with various means of preventing re-emission over very long timescales. In terms of the amount of time that the CO_2 is expected to be sequestered from the atmosphere, storing CO_2 in geological formations and in durable minerals (in solid or dissolved forms) has the highest storage permanence (millennium scale). Alternative options include stabilising biomass carbon through processes such as pyrolysis and storing it in ways that ensure it does not decompose.

These solutions are distinct from another category that is often referred to as "conventional" CDR, or "nature-based solutions". These can include forest management practices, such as afforestation and reforestation, and restoration of peatland and coastal soils that assimilate CO_2. Options that rely on CO_2 storage in vegetation and soil have the lowest storage permanence, tend to be lower cost, and are subject to risks of reversal, such as wildfires, infestations and logging, or certain types of agriculture tilling. Despite continuing uncertainty about their permanence, they are funded at much larger scales than technology-based solutions.

[35] Pathways that rely on CO_2 storage in biomass dispersed in the environment – including in construction wood, biochar in soils and biomass sinking – are not covered due to uncertainties about long-term storage integrity. However, they may meet the criteria for future inclusion if improved measurement confirms their permanence.
[36] In reports and policy documents, the various combinations of these options are classified in different ways, depending on the country and author.

Carbon dioxide removal technology landscape and report scope

Means of removing CO_2 from the atmosphere (e.g. capture)		Means of preventing re-emissions (e.g. storage): Deep underground	Above-ground solid	Dispersed in open environments	In living organisms
Chemically captured as a gas	**From the air**	Direct air capture with geological storage** **TRL7**	Direct air capture with mineralisation in building materials **TRL 5**		
	From the ocean	Ocean capture with geological storage** **TRL 5**	Ocean capture with mineralisation in building materials **TRL 4**		
Geochemically bound in minerals*			Ambient mineralisation in wastes **TRL 5**; Ambient mineralisation in building materials **TRL 7**	Enhanced rock weathering **TRL 5**; Ocean alkalinity enhancement **TRL 5**	
Biologically captured during biomass growth (photosynthesis)	**Capture from biomass fermentation, combustion or gasification**	BECCS via geological storage** **TRL 9**	BECCS via mineralisation in building materials **TRL 7**		
	Biomas pyrolysis	Bio-oil storage **TRL 5**; Biochar storage **TRL 5**		Biochar in soil	
	Treatment to prevent decomposition	Other underground biomass storage*** **TRL 7**	Construction wood	Biomass sinking	
	No treatment				Afforestation; peatland and wetland restoration; ocean fertilisation

Report scope

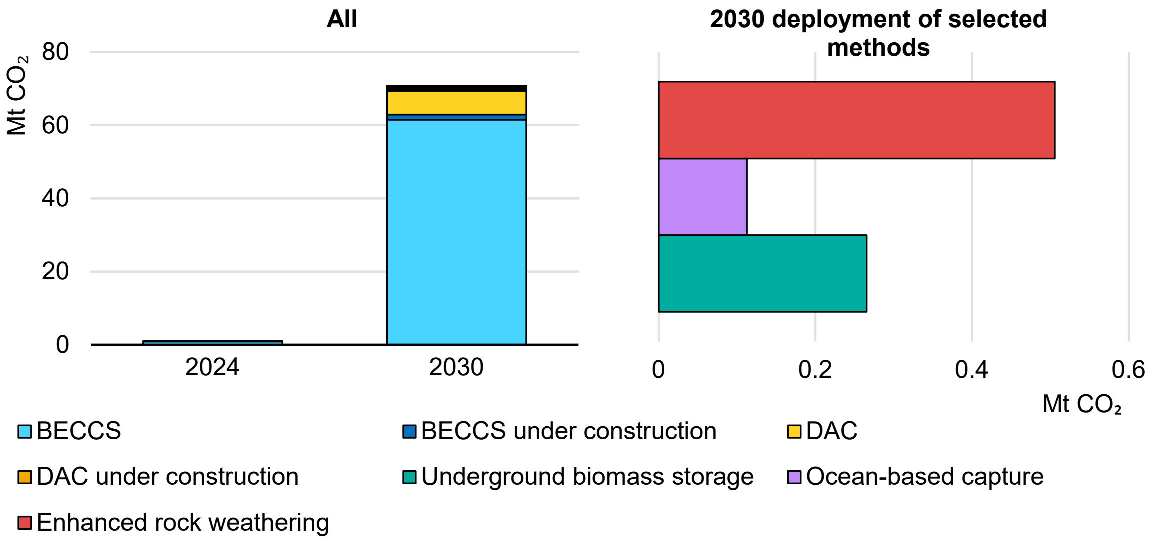
*Generally considered as near-permanent storage regardless of storage method. **Includes subsurface mineralisation in basalts and peridotites. ***Includes underground storage chambers and subterranean injection with potential for permanent removal under certain conditions and for which developed standards currently vary in expected durability, ranging from 100 years to more than 1 000 years. BECCS = bioenergy with carbon capture and storage; TRL = technology readiness level.

While most of the CDR technologies reviewed in this chapter are still at very early stages of development – many do not even have an operational pilot plant – a subset are more advanced. Today, the overwhelming majority of the roughly 1 million tonnes of carbon dioxide (Mt CO_2) of operational capacity is BECCS.[37,38] Based on announcements of planned capacity, the share of DAC is set to grow, but only to around 10% in 2030. Government support currently favours these two more mature technologies, with USD 3.5 billion and USD 1.3 billion of public funding invested in BECCS and DAC, respectively. While current facility-level

[37] On a gross basis that does not account for load factors or life cycle emissions considerations.
[38] As per the diagram, this excludes biochar-based removal.

announcements indicate that other methods are a couple of orders of magnitude smaller in scale, their developers nonetheless have ambitious expansion plans that would narrow the gaps by 2030 if they are successful.

Operational and planned carbon dioxide removal capacity, 2024 and 2030



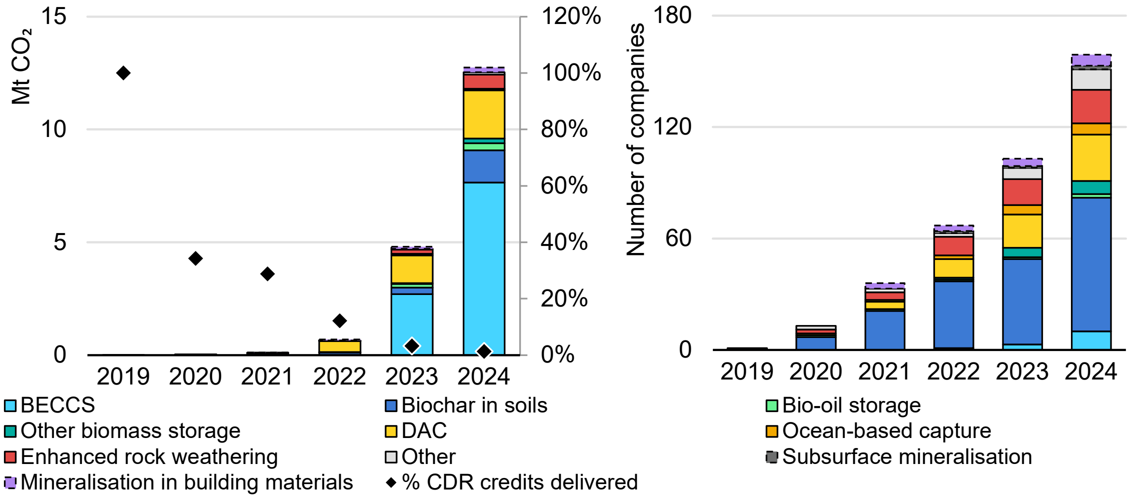
Notes: DAC = direct air capture; BECCS = bioenergy with carbon capture and storage. Announcements generally refer to gross removal capacity, and do not include capacity factors and project-level life cycle emissions which would result in a lower actual removal per year. Numbers are based on facility and project-level announcements and exclude long-term company development scenarios. For example, this excludes Occidental Petroleum's development scenario of building 100 DAC plants by 2035. BECCS gross removal capacity includes the circa 0.5 Mt CO_2 per year sequestered as part of the Illinois Industrial Carbon Capture and Storage which paused injection in October 2024. When the fraction of biogenic emissions out of total captured CO_2 is unknown, it is assumed that the share of biogenic emissions is 10% in cement facilities and 50% in waste-to-energy plants.

Purchasers of credits in voluntary carbon markets are already attracted by the high potentials of DAC and BECCS, as well as their permanence. These two options make up three-quarters of cumulative CDR credits sold in the past 5 years, though the cumulative share decreased for the first time between 2023 and 2024, as other approaches grew, including mineralisation and biomass-based methods, especially biochar, but also underground biomass storage and bio-oil storage. The sold credits are typically for future removals – at the end of 2024, delivered credits represented just 5% of cumulative CDR credits sold. As the technological basis of credits diversifies, measuring the performance of the approaches with become a key area of innovation to support market growth.

Trends in venture capital (VC) investment in CDR and CO_2 storage start-ups also show that start-up activity is growing overall and diversifying, notwithstanding an outsize level of investment in 2022, a year of high activity in the wider VC market (see Chapter 3). There was a near four-fold increase in start-ups and a sevenfold increase in investment between 2019 and 2024. While DAC made up close to

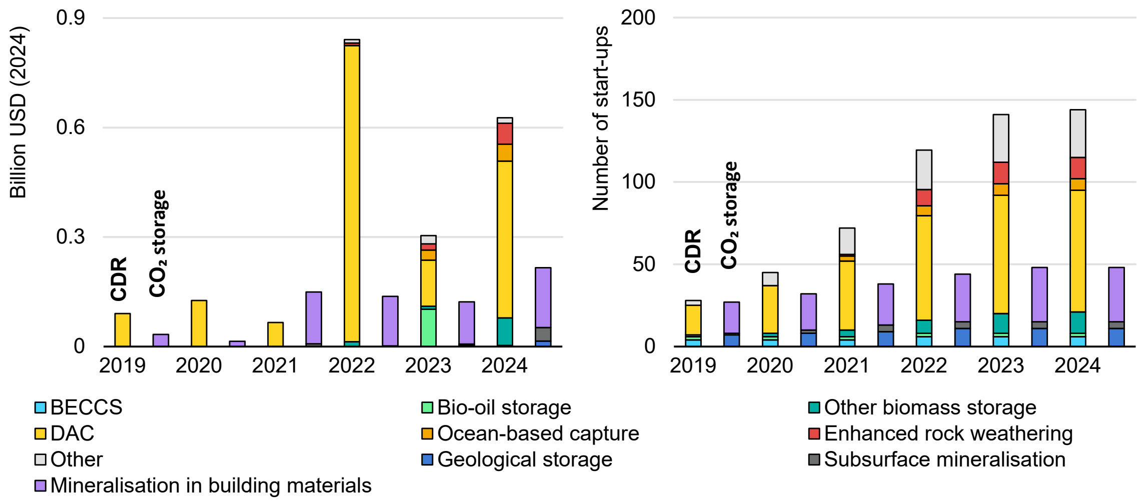
100% of VC investment in CDR in 2022, this value decreased to 70% in 2024 with the growth of biomass-based CDR (13% of VC in 2024), enhanced rock weathering (9%), and ocean-based capture (7%).

Cumulative carbon dioxide removal (CDR) credits sold and percentage delivered for selected CDR approaches (left), and number of companies selling credits (right), 2019-2024



Notes: BECCS = bioenergy with carbon capture and storage; DAC = direct air capture; CDR = carbon dioxide removal. Only novel CDR approaches included, not conventional CDR methods, such as afforestation.
Source: IEA analysis based on CDR.fyi. data (last accessed February 2025).

Annual venture capital investment and start-ups founded in selected carbon dioxide removal (CDR) technologies, and CO_2 storage technologies that could be used for CDR, 2019-2024



Notes: BECCS = bioenergy with carbon capture and storage; DAC = direct air capture; CDR = carbon dioxide removal. Geological storage includes conventional storage in saline aquifers and depleted fields. This chart only includes start-ups working on the subset of CDR approaches and CO_2 storage selected for this report.
Sources: IEA analysis based on CleanTech Group (2024).

CDR approaches span a wide range of costs today and its long-term costs remain highly uncertain. CDR costs for BECCS have been estimated to lie between USD 40 and USD 50/t CO_2 in lignocellulosic biofuel plants and between USD 60 and USD 85/t CO_2 for biomass-fired boilers,[39] but could reach more than USD 300/t CO_2 for greenfield projects if the entire plant cost is allocated to removals. Net removal costs are also highly dependent on project-level life cycle emissions, especially those related to biomass production. Depending on technology type and energy source, the potential long-term costs of removal with DAC have been estimated between USD 100 and 900/t CO_2, though first-of-a-kind costs are expected to be on the upper end of the range, if not higher, as evidenced by CDR credits trading at prices ranging between USD 450-2 050/t CO_2 in 2023. To further complicate estimation, it is possible that an approach that is not the frontrunner today becomes the long-term market leader through learning-by-doing. It is important that all innovators in this area get the opportunity to investigate whether their approach has the potential to significantly drive down costs and increase efficiencies at scale. Well co-ordinated and targeted innovation in CDR technologies is needed now more than ever.

Technology landscape

Biological approaches

Bioenergy with CO_2 capture and storage (BECCS)

Among the technologies covered in this chapter, BECCS is the largest source of CDR to date. In 2024, around 2 million tonnes of carbon dioxide (Mt CO_2) per year was captured from biogenic sources, of which 1 Mt CO_2 was stored in dedicated storage, potentially qualifying for removal. However, careful life cycle assessment (LCA) of the overall value chain, including biomass production, is required to assess the net removal potential of these projects. Based on projects currently in the early and advanced stages of deployment, BECCS removal capacity could reach around 60 Mt CO_2 per year by 2030 in gross terms, making up 90% of the CDR project pipeline. Yet many of these projects remain at feasibility or engineering and design phase, with only 1.5 Mt CO_2 per year of capacity under construction.

Biogenic CO_2 capture is a process in which CO_2 is indirectly captured from the atmosphere, first by being biologically fixed in biomass, then chemically captured from bioenergy facilities that would otherwise emit CO_2 to be subsequently combined with a means of permanent sequestration. The bioenergy facilities can include biofuel and hydrogen production, which produce relatively pure streams of

[39] In these estimates BECCS costs only include the costs of capturing, compressing, transporting and storing CO_2 (and exclude costs associated with bioenergy production).

process CO_2 emissions, or combustion emissions from heat and power generation in power plants, waste-to-energy plants and industrial applications (including co-firing with fossil fuels in the cement and pulp and paper sectors, or oxidation of biochar in the iron and steel sector). Heterogenous feedstocks, as well as contaminants in the flue gas from biomass combustion, can make CO_2 capture from these plants more challenging than from fossil fuel combustion.

Unlike other CDR approaches, the BECCS business environment is mostly composed of plant operators seeking to capture their own emissions, as well as engineering companies or pure-players providing modular capture skids or capture as-a-service. Around 90% of biogenic capture involves CO_2 captured at bioethanol facilities, one of the most mature routes (TRL 9) and lowest-cost BECCS applications due to the high concentration of CO_2 in the process gas stream, with the most recent plant coming online in the United States in 2023. CO_2 capture from upgraders that remove CO_2 from biogas to leave biomethane has also been commercial for several decades, though at a lower unit size, with the largest plants capturing around 70 000 t CO_2 per year. The CO_2 currently captured at such facilities is typically sold for use in the beverage and chemical industries, with the exception of a few small users that make building materials. CO_2 capture at biomass combustion plants has been at the commercial demonstration stage since October 2020 (TRL 7) with the commissioning of a capture unit at Mikawa power station in Japan. In 2023, construction started on the first large-scale BECCS project in Europe, which will become the largest biomass combustion plant equipped with capture in the world. Less mature projects include the demonstration of biomass gasification for synthesis gas and hydrogen applications, seeking to reduce capital costs and increase feedstock flexibility, as well as pilot projects to test advanced capture processes on biomass-fired power plants.

Revenue and funding sources

Over USD 3.5 billion of public funding in the form of capital grants and operational subsidies has been made available to support first-of-a-kind commercial BECCS projects in the last 5 years. Given the sector is dominated by utility companies and a few capture companies, BECCS has historically attracted very little VC investment, making up less than 1% of total VC raised in CDR in the last 5 years, as well as in 2024. Funding of BECCS projects and innovation instead largely relies on direct public support and CDR credit purchases on voluntary carbon markets. Key programmes include:

- Denmark's carbon capture and storage (CCS) and NECCS funds awarded the equivalent of USD 1.2 billion in annual operational subsidies to Ørsted to build a 0.4 Mt CO_2 per year Kalundborg hub (in 2023) and USD 24 million for three additional BECCS projects (in 2024).

- Sweden's BECCS reverse auction programme awarded the equivalent of USD 1.8 billion in operational subsidies to the 0.8 Mt CO_2 per year Stockholm Exergi project in 2025.
- The EU Innovation Fund also awarded funds (equivalent to USD 213 million) to the Stockholm Exergi project. Additional grants for large-scale projects are expected in 2025, with the opening of a new Horizon Europe call specific to BECCS and DAC.
- The United Kingdom's BECCS hydrogen innovation programme has budgeted the equivalent of USD 38 million for R&D and demonstration support for applications involving less advanced technologies, such as CO_2 capture from gasification. Funding was also allocated to eight BECCS projects as part of the Direct Air Capture and Greenhouse Gas Removal Innovation Programme, with a budget equivalent to around USD 90 million.

Advanced offtake agreements for CDR credits represent the second-largest source of funding for these projects. Ørsted and Stockholm Exergi, are currently the single largest sellers of CDR credits, making up 60% of historical CDR purchase deals, the majority of which were signed with US-based multinational Microsoft. This is due to the large sizes of BECCS projects. While the credit price for these two major deals remains unknown, they would amount to roughly the same scale as the public funding received by these companies from governments (USD 1.2 billion and USD 1 billion, respectively, assuming a USD 300/t CO_2 strike price similar to that of a smaller BECCS deal from 2023). In both cases, the private credit deals were instrumental in moving these projects forward, alongside public funds.

Selected developments in biogenic capture in 2023-2025

Technology		Current TRL	Advance	Year	Country	Context
CO_2 source	Capture process					
Sugar and starch fermentation	CO_2 drying and compression	9*	A 200 000 t CO_2 per year CCUS project was commissioned at the Blue Flint ethanol plant, the third-of-its-kind plant in the United States.	2023	United States	Project lifecycle emissions including from corn cultivation need to be carefully accounted for to translate gross CDR capacity into net.
Biogas upgrading	CO_2 drying and compression	9	Neustark started operations on a 1 500 t CO_2 capture unit at SIG biogas plant, with plans to store the CO_2 in construction materials.	2024	Switzerland	Neustark first installed capture prototypes in Switzerland in 2021.

Technology		Current TRL	Advance	Year	Country	Context
CO_2 source	Capture process					
Biomass-fired combined heat and power plant (CHP)	Post-combustion amine-based chemical absorption	7	Construction started on the Kalundborg hub project, aiming to capture 430 000 t CO_2 per year from two Orsted biomass heat and power plants for sequestration in Norway.	2023	Denmark	Once operational, these post-combustion chemical absorption capture units developed by SLB Capturi would increase the TRL of biomass post-combustion capture to 8.
Biomass-fired power plant	Post-combustion solid adsorption	5	A metal organic framework (MOF) demonstration unit was installed at Drax power plant by Promethean Particles, aiming to capture 0.5-1 t CO_2 per day.	2024	United Kingdom	The technology was first piloted at Drax's incubation site in 2022, following a pilot campaign for chemical absorption capture technologies by Mitsubishi Heavy Industries and C-Capture. Drax is the largest biomass-fired power plant in the United Kingdom, and plans to scale up to 8 Mt of CO_2 removal by 2030.
Waste incinerator	Post-combustion amine-based chemical absorption	7 *	SLB Capturi installed a world-first large-scale (100 000 t CO_2) capture unit at Twence waste incinerator.	2025	The Netherlands	SLB Capturi develops standardised modular capture plants of 100 and 400 kt CO_2 per year. The company has also signed a contract with Heidelberg Materials to deliver the first 400 kt CO_2 per year unit at the Brevik cement plant in 2025.
Waste incinerator	Post-combustion amine-based chemical absorption	7 *	A FID was reached on a 350 000 t CO_2 per year capture unit at Hafslund Celsio waste-to-energy plant.	2025	Norway	The unit targets operation in 2029, for CO_2 storage at the Northern Lights storage site. Around 50% of captured CO_2 is of biogenic origin, generating removal.

Technology		Current TRL	Advance	Year	Country	Context
CO_2 source	Capture process					
Waste incinerator	Post-combustion amine-based chemical absorption	5	The country's first carbon capture pilot on a waste-to-energy plant started capturing 1 t CO_2 per day at Enfinium Ferrybridge site.	2024	United Kingdom	The Hitachi Zosen Inova pilot will test the performance of a range of amine solvents over a period of 12 months. If successful, Enfinium has plans to deliver around 1.2 Mt CO_2 of removals per year in the 2030s.
Pulp and paper mill	Post-combustion molten salts chemical absorption	5	Canadian company Kruger invested USD 16 million in a 5 t CO_2 per day demonstration capture unit at a pulp and paper mill.	2024	Canada	The project will demonstrate US start-up Mantel Capture Inc's high-temperature capture technology.

Note: *marks a TRL change in 2023-2024 (or early 2025). Not all projects involve permanent sequestration of CO_2, resulting in BECCS, but are nonetheless relevant to tracking developments in the biogenic capture space.

Underground biomass storage

Underground storage of biomass feedstock has recently received increasing attention as an alternative to BECCS. It has the potential to circumvent some of the complexity of connecting biogenic CO_2 supply with geological CO_2 storage sites, which may not be co-located, and can also enable the use of biomass resources that require fewer emissions-intensive inputs and lead to lower land-use change than conventional bioenergy crops. Underground biomass storage is less mature, with projects mostly led by start-ups at pilot or pre-commercial demonstration scales that are a couple of orders of magnitude lower than BECCS projects. Operational removal capacity is currently just under 30 kt CO_2 per year, with announced project plans for scale-up to over 250 kt CO_2 in 2030.

Approaches involve different ways to stabilise the carbon content in biomass, and then store the result underground in a controlled environment that minimises degradation. These include biomass fast pyrolysis to bio-oil and its injection into geological formations, organic waste slurry injection into salt caverns, and storage of sealed biomass pellets in underground containers or vaults. Pyrolysis conditions can also be adjusted to produce a solid product, biochar, which under anaerobic conditions, for example in anoxic chambers, has the potential to lock CO_2 away for a long time. Given the early stage of deployment for these approaches, developed standards to date consider a range of storage durability, from 100 years and above to 1 000 years and above. As with other CDR approaches, realising the potential will rely on careful monitoring of the engineered storage site.

Only one company, Charm Industrial, a US-based start-up, conducts biomass pyrolysis for bio-oil injection today. While bio-oil injection for CO_2 storage is itself novel, the company relies on established technologies. Fast pyrolysis of biomass to bio-oil for chemicals or energy purposes is proven at commercial scale (TRL 9), with the first commercial-scale facilities dating back to the mid-1990s with the largest facilities processing around 65 000 tonnes (t) of biomass per year. Smaller-scale pilots and demonstrators also seek to test different feedstocks, reactor configurations and catalysts to improve bio-oil yield and quality. In terms of storage, bio-oil injection builds on the same technologies used for oilfield waste slurry injection, a technique that has been employed by the oil and gas waste management industry since the 1980s.

Revenue and funding sources

The sector has mostly benefited from VC investment and advanced CDR purchase agreements in the past 2 years, though CDR funding programmes targeting biomass-based removals are emerging:

- **VC investment**: Around USD 200 million was raised by five companies since 2022, making up 12% of total VC investment in CDR in 2024 and 40% in 2023.
- **Offtake agreements**: given the lower scale of projects, these approaches remain a niche segment of the broader CDR credit market, representing only around 4% of CDR purchase agreements made in the past 5 years, but with volumes significantly increasing as companies expand from pilot to demonstration projects. One of the largest deals to date include one signed between US start-up Vaulted Deep and Frontier, a consortium of technology companies, for the delivery of over 150 000 tonnes of removal through to 2027.
- **Public funding**: the sector is starting to benefit from public funding programmes dedicated to CDR innovation such as the US government's Carbon Negative Shot, which awarded around USD 20 million to three small-scale underground biomass storage pilots in 2024. The technology can also benefit from US funding programmes in advanced bioenergy conversion technology, such as the USD 2 million Bioenergy Technologies Office (BETO) programme.

Selected developments in other biomass storage approaches

Technology	Current TRL	Reported advance	Year	Country	Context
Biomass pyrolysis and bio-oil injection	5	Charm Industrial delivered world's first verified bio-oil CDR credits (105 t) under the Isometric Standard.	2024	United States	The company operates eight small-scale pyrolysis plants and injects bio-oil at the already permitted injection well operated by Vaulted Deep in Kansas.
Biomass storage in underground vaults	7	Graphyte commissioned a 15 000 t per year removal plant in Arkansas.	2024	United States	The company plans to triple the plant's capacity by 2025, and open four additional 50 kt CO_2 plants by 2026.
Biochar storage in underground vaults	5	Carba received USD 7 million in funding for a pilot.	2024	United States	Carba plans to use a pyrolysis technology to convert biomass into charcoal and store it in anoxic conditions in a landfill.
Biomass waste slurry injection	7	Vaulted Deep started injecting biomass waste slurry at its Kansas facility.	2023 and 2024	United States	The company, a spin-off of waste management player Advantek, re-permitted an existing commercial waste injection site in 2023, to inject biomass waste slurry in a salt cavern. It delivered over 9 000 t of removal credits in 2024 alone.

Biochar in soil for CDR

The most common use of biochar today is for application to agricultural soil because of its value as an enhancer of microbial activity, soil fertility and inhibitor of nitrous oxide (N_2O) emissions. These characteristics translate into economic value for biochar producers but make the CDR impact difficult to verify given the open nature of such CDR systems. Similar monitoring concerns are also relevant to techniques that involve depositing biomass in stable deep ocean or sea-floor settings ("biomass sinking").

Biochar in soils is today the largest provider of CDR credits (around 85% of cumulative delivered credits to date), the third-largest seller of removal credits after BECCS and DAC (around 11% of CDR purchase deals in the last 5 years), and has gross CDR capacity roughly on par with BECCS (~0.8 Mt CO_2 in 2023). Bolivian company Exomad Green operates two of the largest biochar production plants in the world in Bolivia, each with the capacity to produce over 20 000 tonnes of biochar per year, which represents around 60 000 t CO_2. A second plant was commissioned in 2024, for which the company plans a doubling of production capacity to 120 000 t CO_2 in 2025. Canadian company Carbonity also announced a 10 000 tonnes of biochar per year plant to be commissioned in Canada in 2024, with plans to scale up production to reach 30 000 tonnes of biochar production a year in 2026. Other large-scale biochar plants are in operation in Brazil (4 500 tonnes per year) and under construction in the United Kingdom (9 000 tonnes per year).

The difficulty of observing biochar degradation in natural conditions under long timeframes means that its CDR permanence continues to be debated. Most measurement studies span 3-5 years, with a max around 8.5 years. While consensus had pointed to centuries to thousands of years for the degradation of biochar, recent research has estimated that the half-life of biochar is 100 million years at ambient temperatures of 30 °C, and much longer for lower temperatures.

R&D and demonstration priorities include:

- Continue efforts to verify storage permanence and develop guidelines for how to translate different practices into confidence levels for 10 000-year removals.
- Continue research into local impacts on soils.
- Develop advanced pyrolysis processes that maximise carbon conversion efficiency and biochar durability. The share of biomass feedstock that ends up fixated in biochar also depends on the scale and type of biochar production, with current carbon efficiencies from commercial pyrolysis production ranging from 5% to 55%. Co-locating small modular pyrolysis units at sources of waste biomass can also enable larger biomass waste availability.
- Measurement at scale: develop systems to monitor open environments at scale and expand the use of LCA software and remote sensing for real-time data on biomass and biochar supply chain sustainability.

Chemical approaches

Direct air capture

Direct air capture (DAC) is the CDR sector that has seen the most activity in the past 10 years, with the number of start-ups growing sevenfold, and over 140 companies now developing DAC solutions. To date, almost 30 DAC plants have been commissioned in Europe, North America, Japan and the Middle East. Most of these plants are small-scale, with only five plants capturing more than 1 000 t CO_2 per year and a combined capture capacity of over 17 000 t CO_2 per year, and with only a few commercial agreements in place to sell or store the captured CO_2. The remaining plants are operated for testing and demonstration purposes. According to projects under development today, DAC gross removal capacity could reach around 7 Mt CO_2 by 2030.[40]

DAC refers to the chemical or physical separation of CO_2 from ambient air through a capture medium or mechanical air contactor so that it can be used or stored. Having grown from only around ten start-ups in 2015, the sector now encompasses a fast-growing range of technology approaches, with various degrees of maturity. As with other types of CO_2 capture, the compressed CO_2 can be converted into products such as fuel or chemicals, but DAC is only considered as a CDR technology when it involves long-term storage of the CO_2. These approaches differ by their capture medium type (solid sorbent, liquid solvent, membrane, cryogenic) and regeneration method (temperature, vacuum, moisture, electrochemical). One of the most mature approaches to date is using amine-functionalised solid sorbents regenerated at low-temperature and pressure (vacuum).

Also emerging are DAC technologies relying on innovative separation systems, which are at various stages of development, with the main goal being to reduce the energy intensity of the processes. Advances in innovative solid sorbents, such as calcium oxide sorbents, MOFs and zeolites, include the commissioning of US start-up Heirloom's facility in the United States and the first operational DAC pilot relying on zeolites commissioned by Norway-based firm Removr. Electro swing adsorption (ESA)-DAC, which uses an electrochemical cell to absorb CO_2, is also currently being developed in the United States and United Kingdom.

Revenue and funding sources

DAC has benefited from substantial private investment and public funding in the past decade. However, beyond the purchase of Carbon Engineering by Occidental Petroleum in 2023 and Swiss company Climeworks raising around USD 900 million in equity, most DAC companies today remain small-scale start-ups with limited resources relative to the high upfront capital costs of large-scale DAC facilities. Advanced offtake agreements have been equally key to help finance first-generation DAC facilities, with DAC credits trading at an average price of USD 700/t CO_2 in 2023, paving the way for second and third-generation DAC technology providers selling credits at lower prices today (DAC credit price index averaging USD 500/t CO_2 as of February 2025). While a good indicator that the DAC space is diversifying, credits are still likely to be lower than actual cost of removal for most operating plants today. Key funding streams include:

[40] This excludes Occidental's development scenario of deploying 100 DAC plants by 2035.

- **VC investment:** around USD 1.7 billion invested in DAC companies (around 80% of total VC in CDR) in the past decade.
- **Offtake agreements:** DAC makes up 17% of purchase deals in the last 5 years. Large purchase agreements in 2024 include 1pointFive's deal with Microsoft for 500 000 t CO_2, and Holocene's deal with Google for 100 000 t CO_2, the first with a USD 100/t CO_2 price point.
- **Public funding:** DAC projects around the world have received around USD 1.3 billion of public funding. The large majority of it comes from the US DoE USD 3.5 billion Regional DAC hubs programme, which has so far selected two hubs to negotiate combined funding of USD 1.2 billion. As part of this programme, a further USD 1.8 billion call was announced in December 2024 to fund the design and construction of mid- and large-scale DAC facilities. Other notable government funding includes a grant from the Canadian government equivalent to around USD 19 million for Carbon Engineering to develop a DAC R&D facility. Funding was also allocated to 11 DAC projects as part of the UK Direct Air Capture and Greenhouse Gas Removal Innovation Programme.

Selected developments in direct air capture (DAC) in 2023-2024

Technology	Current TRL	Reported advance	Year	Country	Next step
Liquid, temperature regeneration	6	Occidental Petroleum started construction on a 500 000 t CO_2 per year DAC plant in Texas.	2023	United States	Once commissioned in 2026, this will be the first-of-a-kind liquid DAC plant operating at commercial scale. Successful operation will raise it to TRL 8.
Solid: amine-functionalised sorbent; temperature & vacuum regeneration	7	Climeworks commissioned the first 12 collectors of the Mammoth plant with a combined removal capacity of 6 000 t CO_2 per year, the largest DAC plant to date.	2024	Iceland	Climeworks aims to complete the installation of 60 additional collectors this year, reaching a combined capacity of 36 kt CO_2 per year, close to ten times larger than its predecessor plant, Orca.
Solid: amine-functionalised sorbent; temperature & vacuum regeneration	5	Successful operation of AirCapture pilot at National Carbon Capture Center.	2024	United States/ Oman/ United Kingdom	The test campaign demonstrated Air Capture's technology. Construction also started on 500 t CO_2 per year project Hajar, a partnership between AirCapture and 44.01, for CO_2 mineralisation in peridotite in Oman.
Solid: amine-functionalised sorbent; temperature & vacuum regeneration	5	Octavia Carbon started construction on its 250 t CO_2 removal per year DAC demonstration plant, targeting commissioning in 2025.	2024	Kenya	Project plans to expand capacity to 1 000 t CO_2 per year, leveraging geothermal energy potential from the Great Rift Valley, and planning to store CO_2 in underground basalts with subsurface mineralisation company Cella Mineral.

Technology	Current TRL	Reported advance	Year	Country	Next step
Solid: calcium oxide sorbent; temperature & vacuum regeneration	5	Heirloom commissioned a 1 000 t per year DAC plant for CO_2 mineralisation in concrete materials with technology partner CarbonCure.	2023	United States	
Solid: Zeolites; temperature regeneration	5	Removr launched a 300 t CO_2 per year pilot at Norway Technology Centre Mongstad.	2024	Norway	The company plans to scale the pilot to 2 000 t CO_2 per year in 2025 and commission a first large-scale facility with a capacity of 30 000 t per year in 2027.
Multiple		The world's first DAC open-access technology test centre was commissioned at the US DoE National Energy Technology Laboratory.	2024	United States, Canada	The test centre has announced its first partnerships. In Canada, a 3 000 t CO_2 per year test centre also started construction.

Ocean-based capture

Also referred to as "Direct Ocean Capture" or "Direct Ocean Removal", this technique has received increasing attention in the past 2 years as part of a wider group of marine CDR approaches. While operational capture capacity is small today (just around 500 t CO_2), it could reach around 110 000 t CO_2 per year in 2030 if announced company projects are realised.

This approach involves passing seawater through electrochemical systems to create a pH gradient that facilitates capture of CO_2. This enhances the ocean's capacity to absorb additional atmospheric CO_2, thereby reducing the concentration of CO_2 in the air. While different technologies are being trialled at lab scale, only a handful of companies are now starting to deploy the technology at pilot and early-demonstration phase. These efforts focus on proving the technical feasibility, cost-effectiveness, and scalability of ocean-based capture in real-world environments.

Revenue and funding sources

Funding for ocean-based capture has been so far driven by interest from VC, philanthropic organisations, and corporate carbon removal programmes:

- **VC investment**: the sector has received around USD 70 million of VC investment since 2023, making up around 3% of total cumulative CDR VC investment.
- **Public funding**: in the United States, the Marine Carbon Dioxide Removal (mCDR) programme, launched in 2023, has a USD 36 million budget for 11 projects developing models and advanced technologies to assess marine CDR.

Funding was also allocated to two ocean-based capture projects as part of the Direct Air Capture and Greenhouse Gas Removal Innovation Programme in the United Kingdom.

- **Offtake agreements**: ocean-based capture still represents a small share (<1%) of CDR credit purchase deals in the last years because of the early stage of the technology, with one major purchase agreement signed for 62 000 CDR credits between US start-up Equatic and US aircraft manufacturer Boeing in 2023.

Selected developments in ocean-based capture, 2023-2024

Technology	TRL	Reported advance	Year	Country	Next step
Seawater electrolysis	5	Equatic commissioned phase 1 (1 t CO_2 removed per day) of its first demonstration plant in Singapore. A second phase reaching 3 650 t CO_2 per year should follow in 2025.	2024	Singapore/ Canada	Engineering is underway for the first commercial site in Quebec in 2026, targeting a capacity of 109 500 t CO_2.
Bipolar-membrane electrodialysis	5	Captura announced a 1 000 t per year pilot facility to be installed at the Hawaii Ocean Science and Technology Park after the successful operation of its 100 t and 1 t per year pilots in California.	2024	United States	In partnership with Norwegian energy company Equinor, the facility was commissioned in February 2025.
Seawater electrolysis	5	The SeaCURE 100 t CO_2 per year pilot started operation at the SEA LIFE centre in Weymouth.	2025	United Kingdom	The project received the equivalent of a USD 3.7 million grant.

Geochemical approaches

Ambient CO_2 mineralisation

The process of accelerated ambient CO_2 mineralisation underpins several CDR and other CO_2 storage approaches. Some, such as mineralisation in building materials, have already been deployed at commercial scale. Since the 1990s, R&D has been conducted into ambient CO_2 mineralisation for CDR but it remains at the small-scale pilot stage. Removal capacity through these approaches is currently just over 4 000 t CO_2 but could reach around 500 000 t CO_2 per year in 2030 according to company announcements.

Ambient CO_2 mineralisation involves the accelerated uptake of atmospheric CO_2 in alkaline materials through the crushing and mixing or spreading of these materials to increase their surface area, thereby enhancing their natural capacity to absorb and store CO_2. The alkaline materials used, the medium in which they are incorporated (closed or open system), and the ultimate form in which the CO_2 is stored (solid carbonates or dissolved bicarbonates) vary between approaches. Suitable materials can include mined rocks (e.g. basalts, peridotites), mine tailings, and industrial waste (e.g. asbestos tailings, steel slag and cement kiln dust).

The leading closed-system approach consists of increasing natural CO_2 absorption in alkaline waste materials on industrial sites through crushing, activation and stirring of these rocks. Rock activation is a critical step to increase the rock's CO_2 absorption rate, and includes chemical, mechanical, thermal, and hybrid techniques. Canadian firm Arca leads the commercialisation of CO_2 mineralisation in mine tailings, using microwave radiation to activate serpentine mine tailings and stirring these rocks to maximise contact area, thereby increasing CO_2 absorption rates.

In open-system approaches, such as enhanced rock weathering (also called terrestrial enhanced weathering or coastal enhanced weathering), rocks are crushed and spread on land. When they are dispersed in marine environments this is known as ocean alkalinity enhancement. In both cases, the crushed rocks increase alkalinity and enhance the natural capacity of the environment to assimilate CO_2 in the form of dissolved bicarbonates, ultimately in groundwater and oceans. Field trials involving the spreading of silicate rocks on farm land are under way in various countries, with Eion and Lithos in the United States, UNDO in the United Kingdom and Canada, Greensand in the Netherlands, and Terradot and InPlanet in Brazil, and Alt Carbon in India. CarbonRun and Planetary Technologies are leading the development of alkalinity enhancement in river and marine ecosystems, with trials ongoing in Canada, while US-based Crew Carbon carries out mineralisation at wastewater treatment facilities.

Revenue and funding sources

Funds have mostly come from research grants supporting foundational research into mineral weathering rates, ecological impacts, and methods for monitoring carbon sequestration. However, there is growing interest from VC investors for larger-scale trials:

- **Public funding**: research programmes such as the Carbon Negative Shot in the United States and the US Department of Agriculture Partnerships for Climate Smart Commodities help support enhanced mineralisation projects on industrial sites and in open ecosystems, with around USD 20 million allocated to five small-scale enhanced rock weathering pilots through both programmes in 2022 and 2024. The UK Direct Air Capture and Greenhouse Gas Removal Innovation Programme also awarded three enhanced rock weathering and ocean alkalinity enhancement pilot projects.

- **Offtake agreements**: the sector made up around 5% of CDR credits offtake agreements in the past 2 years, with major deals including 200 000 tonnes of CDR credits purchased by Google from company Terradot, and over 150 000 tonnes purchased by Frontier from company Lithos Carbon.
- **VC**: enhanced rock weathering has raised around USD 80 million since 2022, making up about 4% of total cumulative VC going into CDR. Three companies – Terradot, Lithos Carbon, and UNDO – have gathered most of the investment. Start-ups exploring the potential of ocean or river alkalinity enhancements at an earlier stage of development have yet to raise substantial capital.

Selected developments in ambient CO_2 mineralisation approaches

Technology	Current TRL	Reported advance	Year	Country	Next step
Ambient CO_2 mineralisation in alkaline wastes	5	Arca announced new 18-month mineralisation pilot at BHP Mt Keith Nickel West Mine in Australia, funded by a USD 0.9 million grant by the BC Centre for Innovation and Clean Energy.	2023-2024	Australia	In 2024 the company opened the "carbon sandbox project" to test its measurement technology.
Enhanced rock weathering		AltCarbon opened its Darjeeling Climate Action Lab Bagdogra, a state-of-the-art facility dedicated to advancing research.	2024	India	Lab aims to process up to 600 000 samples annually by 2025, carrying out precision analysis including isotope analysis, inductively coupled plasma optical emission spectroscopy (ICP-OES) and X-ray diffraction.
Enhanced rock weathering	5	Results from a large-scale 4-year field trial on maize and soybean fields in the US corn belt concluded that both significant CDR rates and yield increase could be achieved.	2024	United States	The field trial used Eion-patented soil fingerprinting technology.
Ocean alkalinity enhancement	5	Vesta launched its second alkalinity enhancement pilot offshore of Duck, North Carolina, aiming to remove 5 000 t CO_2 over the project lifetime.	2024	United States	The aim of the field trial is to quantify the rate at which olivine sand dissolves, and the efficiency of carbon removal in a natural setting, and measure environmental impacts.

Technology	Current TRL	Reported advance	Year	Country	Next step
Electrochemical alkalinity enhancement	4	Ebb Carbon commissioned a 100 t CO_2 pilot at the Pacific Northwest National Laboratory marine facility.	2023	United States	The company recently secured permits for a 1 000 t CO_2 pilot in Port Angeles.
River alkalinity enhancement	5	CarbonRun launched the first river alkalinity enhancement trial in Nova Scotia.	2024	Canada	

Storing captured CO_2

Conventional geological formations

Decades of safe CO_2 injection into the subsurface in saline aquifers and depleted gas fields demonstrate that CO_2 can be secured underground with high permanence under the right conditions. Available global geological CO_2 storage could jump from around 50 Mt CO_2 in 2024 to 70 Mt CO_2 in 2025, based on projects currently under construction. Available capacity could reach 670 Mt CO_2 per year by 2030 if announced projects are developed in full and on time.

Geological storage involves injecting captured CO_2 deep into the subsurface where it is trapped in permeable rock formations. These formations can be divided into three main categories: saline formations, depleted oil and gas fields (areas with one or more reservoirs), and unconventional storage resources (basalts and peridotite rocks, un-mineable coal seams and organic shales). Dedicated CO_2 storage in saline formations is at the most advanced stage, currently at TRL 9, with ongoing injection in nine large-scale projects, including Gorgon CCS in Australia, Quest CCUS in Canada, Illinois Industrial CCS in the United States and the Sleipner and Snøhvit projects in Norway, with first injection dating from 1996 in Norway, and the latest project coming online in the United States in 2023. CO_2 injection in oil and gas fields for the purpose of enhanced oil recovery has been commercial for decades, but first-of-a-kind projects for CO_2 injection in depleted gas fields for dedicated storage were only commissioned in 2024.

Revenue and funding source

Most storage projects that have been commissioned or are under construction are large, multi-billion investment projects developed by oil and gas companies. These projects have benefited from public funding in the form of subsidies and grants in the last decade. Important programmes include:

- The US 45Q tax credit which can cover costs for recently commissioned projects capturing CO_2 from bioethanol facilities and injecting it in nearby saline formations.
- The US government's Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative provides substantial R&D and demonstration support at various phases of CO_2 storage development, including site screening, selection, characterisation and design, and development and construction. In 2024, CO_2 storage projects received over USD 518 million through the third phase of the programme.
- The UK government has confirmed the equivalent of USD 28 billion for two large-scale CCUS hubs confirmed in 2024, which supported a final investment decision in late 2024 for a major offshore saline aquifer storage project.
- The European Union's Connecting Europe Facility-Energy can support CO_2 storage projects, among other infrastructure types, and awarded a sum worth over USD 250 million to support the construction of three projects and the funding of nine preparatory studies in early 2025. In 2022 and 2023, the equivalent of USD 690 million in total was awarded for CO_2 storage.
- In July 2024, the Japanese government's Organisation for Metals and Energy Security (JOGMEC) selected nine CCUS hubs as Advanced CCS Projects,, targeting commercial operation by 2030.
- Governments have also supported first-of-a-kind projects in their countries with direct funding, as exemplified by Canada's award of grants equivalent to USD 680 million for the Quest project in 2015 and Norway's estimated state aid of the equivalent of USD 1.1 billion for the Northern Lights project in 2020.

Selected developments in geological storage of CO_2 in conventional resources

Technology	Current TRL	Reported advance	Year	Country	Next step
Depleted gas field (onshore)	8 *	Santos commissioned its 1.7 Mt CO_2 per year depleted gas field storage project, the world's third-largest dedicated storage project.	2024	Australia	The project plans to expand to a 20 Mt CO_2 per year multi-source CO_2 storage hub.
Depleted gas field (offshore)	7	ENI started capture and injection of 25 000 t CO_2 per year in a depleted gas field offshore Italy with as part of the Ravenna CCS project.	2024	Italy	Ravenna CCS could expand to 4 Mt CO_2 per year by 2030.

Technology	Current TRL	Reported advance	Year	Country	Next step
Depleted gas field (offshore)	7	World's first cross-border CO_2 shipment was injected for dedicated storage in the North Sea as part of the Greensand Project pilot, followed by a final investment decision taken by INEOS.	2023-2024	Denmark	The project aims to store 0.4 Mt CO_2 per year in the North Sea by 2026 with potential to scale up to 8 Mt CO_2 per year by 2030.
Saline aquifer (offshore)	9	Final investment decision for Northern Endurance Partnership, the world's largest dedicated storage project to date.	2024	United Kingdom	The project aims to store 4 Mt CO_2 per year by 2028, with the potential to scale up to 23 Mt CO_2 per year by 2035.
Saline aquifer (offshore)	9	Construction of the world's first CO_2 shipping terminal and largest European storage was completed as part of the Northern Lights Project.	2024	Norway	CO_2 injection should start in 2025, with first shipment received from Heidelberg Materials cement plant in Norway.

Note: *marks a TRL change in 2024.

Subsurface mineralisation

Subsurface mineralisation is at an earlier stage of development than other forms of geological CO_2 storage. If projects in the pipeline are realised, global CO_2 storage capacity in basalts and peridotites could grow from around 20 kt CO_2 per year today to 2.5 Mt CO_2 per year by 2030.

Also referred to as "in-situ mineralisation", this approach involves injecting CO_2, either in supercritical state or dissolved in water, into underground igneous rock formations rich in reactive minerals. Over time, the CO_2 chemically binds with these minerals, effectively storing it as solid carbonates. It was first piloted in basalts by Carbfix Consortium in Iceland in 2012, and supercritical CO_2 injection was also demonstrated in the early 2010s by a US national laboratory at a scale of 1 000 tonnes. Dissolved CO_2 injection continues at the Hellisheiði geothermal plant in Iceland at a rate of 12 kt CO_2 per year with plans to scale up to 34 kt CO_2 per year through Project Silverstone. Carbfix has also been storing CO_2 captured from Climeworks's DAC plant in Iceland, with plans to scale up to 40 kt CO_2 per year with the commissioning of Mammoth. The company has also announced the development of the Coda terminal for storing 700 kt CO_2 per year in 2028 and 3 Mt CO_2 per year in 2032. Company 44.01 has conducted three pilots to inject dissolved CO_2 into peridotite formations in Oman, and stored 10 t CO_2 in 2024 in Abu Dhabi.

Revenue and funding sources

The sector is still relatively nascent, with only a handful of companies and limited funding resources other than public funding available for geological CO_2 storage. As subsurface mineralisation companies do not provide stand-alone removals, private financing from CDR purchase deals mostly go through CDR companies they partner with. There are also currently no public funding programmes dedicated to in-situ mineralisation, though projects can benefit from support from existing CCUS/geological CO_2 storage support that includes in-situ mineralisation in its scope:

- The US government's CarbonSafe programme allocated USD 8 million to feasibility studies for the HERO Basalt Project in 2023.
- The EU Innovation Fund awarded the equivalent of USD 120 million to Carbfix in 2023 and around USD 5 million in 2021.

The sector has also benefited from private funding both through VC investment, with around USD 40 million raised in the last 3 years, and philanthropy, such as from the Earthshot Prize, which awarded the equivalent of USD 1.3 million to 44.01 in 2022.

Selected developments in subsurface mineralisation

Technology	TRL	Reported advance	Year	Country	Next step
Subsurface mineralisation (dissolved CO_2 injection)	7	Climeworks and Carbfix certified the first CDR credits through DAC and in-situ mineralisation under the Puro standard.	2024	Iceland	While a world first, this is less than 1% of the circa 230 kt CO_2 worth of CDR credits that the company has sold so far.
Subsurface mineralisation (dissolved CO_2 injection)		The HERO Basalt project in Oregon received USD 8 million for feasibility studies by the CarbonSAFE phase II programme.	2023	United States	Over the next 2 years, the project aims to drill a stratigraphic well and complete injection feasibility studies, in partnership with Carbfix.
Subsurface mineralisation (dissolved CO_2 injection)	5	ADNOC and 44.01 successfully stored 10 t CO_2 in 100 days in Fujairah mineralisation pilot.	2024	Saudi Arabia	Project aims to scale up to inject more than 300 t CO_2 in a first phase.
Subsurface mineralisation (dissolved CO_2 injection)	4	Cella Mineral announced new 1 000 t CO_2 per year mineralisation pilot in Kenya.	2024	Kenya	
Subsurface mineralisation (dissolved CO_2 injection)	4	Block Energy and Indorama Corporation launched laboratory studies for dissolved CO_2 injection into zeolites.	2024	Georgia	The company plans to start pilot injection in 2025.

Mineralisation in building materials

This approach is relatively advanced compared to subsurface mineralisation, with at least 30 companies operating CO_2 carbonation or concrete curing facilities at commercial scale for a decade. However, commercial scale in this sector is a couple of orders of magnitude below that of geological CO_2 storage. Nonetheless it could constitute a CO_2 storage opportunity for small-scale and dispersed emitters.

Also referred to as "ex-situ mineralisation", or "accelerated carbonation", mineralisation in building materials involves the injection of concentrated CO_2 (pure, or as part of a flue gas) in ways that chemically bind it into solid materials, such as concrete, cement or aggregates. It typically involves reacting CO_2 with calcium- or magnesium-rich minerals, industrial byproducts, or recycled construction materials in controlled environments to produce carbonate minerals. These carbonates are then incorporated into building aggregates or other construction materials. In North America, Fortera, Solidia Technologies, and Carbon Cure lead the development and commercialisation of carbonated concrete production through CO_2 curing, using a range of CO_2 streams, both fossil and biogenic. Other companies solely target the use of biogenic or air CO_2 to benefit from revenues from CDR credits. OCO Technology injects CO_2 from biogas upgraders and distilleries in three curing facilities in the United Kingdom, providing around 20 000 t of net CO_2 removal per year. Neustark in Switzerland operates on the same model, providing around 2 000 t of CO_2 removal per year.

Revenue and funding sources

Funding and market interest in CO_2 storage through building aggregates have been strong, supported by VC, corporate partnerships and government incentives:

- **VC**: Over USD 700 million of VC funding has been invested in ex-situ mineralisation companies since 2010, with Fortera, Solidia Technologies, CarbonCure, bioMASON, and Neustark making up three-quarters of total investment.
- **Offtake agreements**: on the demand side, the sector is also benefiting from purchase agreements for CDR credits, with Neustark, CarbonCure, and OCO Technology making up the majority of sold CDR credits, and with a recent deal signed between Microsoft and Neustark in 2024 for 27 600 t of CO_2 removal.
- **Other private funding**: In 2021, the Carbon XPRIZE awarded USD 20 million to CarbonCure and CarbonBuilt, two North American companies.
- **Public funding**: In 2023, the United States announced up to USD 100 million in funding for CO_2 utilisation projects as part of the Carbon Utilization Procurement Grants programme, though the funding has yet to be allocated. Other public funding programmes have supported projects in Australia, Austria and Canada.

Selected developments in mineralisation in building materials

Technology	Current TRL	Reported advance	Year	Country	Next step
Mineralisation in building materials (fossil/industrial CO_2)	9	Fortera commissioned its first-of-a-kind plant capturing CO_2 from a cement kiln and mineralising it in calcium carbonates.	2024	United States	
Mineralisation in building materials (biogenic CO_2)	7	Neustark started operations on a 1 500 t CO_2 per year capture unit at SIG biogas plant, with plans to store the CO_2 in construction materials.	2024	Switzerland	Neustark first installed capture prototypes in Switzerland in 2021.
Mineralisation in building materials (DAC CO_2)	5	OCO Technology and Mission Zero Technologies to commission first-of-a-kind 250 t per year DAC to building aggregates system at Wretham facility.	2024	United Kingdom	
Mineralisation in building materials (fossil/industrial CO_2)	7	RHI Magnesita, MCi Carbon and partner research institutions received funding for a 50 000 t CO_2 per year mineralisation project at a refractory plant Hochfilzen.	2025	Austria	The project received USD 4 million as part of the Australia-Austria Industrial Decarbonisation Demonstration Partnership Program and aims to be operational by 2028.

Knowledge gaps to be filled

This chapter presents a snapshot of the current state of development of CDR technologies within each technology category, as evidenced by a wave of recent developments. As the different options move up the TRL scale, new questions and needs will arise in relation to performance, regulation and costs. Some of these can be anticipated now, while others will emerge and require swift responses if they are not to become bottlenecks to adoption. Addressing these needs will require proactive action by governments and a collective effort by the scientific community and companies developing CDR projects. The key priorities outlined below encompass both R&D and demonstration needs, and requirements for more accessible information from projects:

R&D and demonstration needs for carbon dioxide removal technologies

Necessary technology improvements for CDR vary across technologies but are primarily focused on reducing costs by minimising energy use and optimising plant designs, as well as developing sensors and digital tools to scale up measurement of CDR in open systems. Artificial intelligence (AI) and machine learning techniques could support these technological developments, for example through accelerated screening of advanced CO_2 capture materials, or improved geochemical modelling of weathering processes.

Research is needed on an ongoing basis to assess the impacts on land use, water availability and other environmental and biological considerations over time, as well as on the broader impacts of CDR to the carbon cycle. Researchers could help to reduce land constraints by developing crops that take up and sequester carbon more efficiently in soils. Research needs also extend to the storage of treated biomass, for which the leakage of carbon over time through unanticipated degradation needs further investigation to ensure the integrity of any removals, and on the impacts of removing CO_2 from the oceans on aquatic ecosystems.

Full life cycle assessments can provide more transparency to better inform policy makers supporting CDR, and buyers of CDR credits. For example, increased deployment of biomass-based CDR approaches requires a comprehensive assessment of land availability and use requirements of biomass feedstocks and their supply chains. This should be supported by comprehensive baselines and guidelines for how estimates for the removal of CO_2 are based on atmospheric drawdown, rather than on displacement of emissions.

R&D and demonstration needs for selected CDR and CO_2 storage approaches

Methodology	Research gaps	Technology gaps
BECCS	• Assess and harmonise environmental and social impacts of scaling-up biomass production and supply chain. • Assess environmental impacts of solvent degradation for chemical absorption. • Identify biomass species that can be grown on degraded land.	• Improve carbon yield of biomass feedstock to minimise environmental impacts of biomass production. • Demonstrate innovative biomass conversion processes that can enhance feedstock flexibility and reduce costs – such as large-scale gasification and chemical looping. • Demonstrate high capture rates on biogenic streams for a range of feedstock compositions to maximise carbon removal. • Develop innovative capture processes to reduce costs and energy requirement.
Bio-oil storage	• Assess environmental and social impacts of scaling-up biomass production and supply chain. • Understand long-term impacts of bio-oil storage. • Identify biomass species that can be grown on degraded land.	• Improve carbon yield of biomass feedstock to minimise environmental impacts of biomass production. • Optimise design and operation parameters of pyrolysis process to maximise carbon conversion rate and minimise energy usage. • Exploit synergies with biochar production.

Methodology	Research gaps	Technology gaps
Other biomass storage	• Assess environmental and social impacts of scaling-up biomass production and supply chain. • Research long-term benefits associated with waste removal (biowaste slurry injection). • Research permanence of biomass storage in open environments. • Identify biomass species that can be grown on degraded land.	• Improve carbon yield of biomass feedstock to minimise environmental impacts of biomass production.
Direct air capture	• Research potential environmental impacts (e.g. land, water, emissions) of scaling up DAC. • Assess environmental impacts of solvent degradation for chemical absorption.	• Develop innovative, stable and recyclable materials. • Develop and improve processes that reduce energy consumption. • Assess technology performance in a wider range of climates.
Ocean-based capture	• Understand the environmental impacts of CO_2 removal on marine ecosystems, particularly in relation to localised changes in water chemistry, such as pH and alkalinity shifts.	• Reduce energy intensity of extraction processes and of associated costs to make the technology viable at scale. • Expand the use of remote sensing technologies (airborne, satellites) to monitor environmental changes and inform diagnostic and regional modelling. • Develop better monitoring, reporting and verification (MRV) technologies to measure removed CO_2.
Ambient mineralisation in wastes; enhanced rock weathering; ocean alkalinity enhancement	• Research potential ecological impacts on marine or terrestrial ecosystems. • Assess the scalability of alkaline material supply, with better data on their location and availability. • Improve understanding and data on the kinetics of mineralisation in different alkaline feedstocks. • Develop better MRV approaches and models to measure removed CO_2.	• Reduce energy demand of activation technologies for on-site mineralisation applications. • Develop and test technologies and sensors to scale up measurement and reduce costs of MRV, particularly for open systems (enhanced rock weathering, ocean alkalinity enhancement).
CO_2 storage in conventional geological formations	• Identify CO_2 storage resources and provide access to necessary data, e.g. through atlases, which are missing in many areas of the world. • Conduct source-sink matching studies to help ensure there is rate matching between capture and storage sites. • Improve basin-scale storage resource monitoring and management.	• Expand use of machine learning for plume modelling, injection well design optimisation, and legacy well assessment to improve processes and reduce costs of site assessment and storage monitoring. • Expand use of advanced monitoring technologies such as fibre optic sensing.

Methodology	Research gaps	Technology gaps
Subsurface CO_2 mineralisation	• Accelerate the reaction of CO_2 mineralisation in basalts and ultramafic rocks. • Research impacts of the generation of carbonate minerals on CO_2 storage efficiency and storage integrity.	
CO_2 mineralisation in building materials	• Assess material availability and supply chains, particularly for calcium- and magnesium-rich feedstocks. • Investigate long-term integrity and performance of CO_2-cured materials relative to conventional cement and concrete. • Research lifecycle effects, particularly for end-of-life treatments.	• Increase capture rate and decrease energy consumption, e.g. through AI-generated surrogate models of reactors to dynamically optimise capture processes. • Improve mixing processes that can account for a high variability of waste streams.

Note: For a comprehensive list of research gaps in CDR see Carbon Gap (2025), CDR Research Gaps Database.

Transparency on data collection through measuring and monitoring technologies and their costs

Unlike other products on the market, the value of CDR to customers lies in its efficacy at removing something invisible. Reliable measuring (or monitoring), reporting and verification (MRV) is essential for each CDR asset during its operation and often for many years after operations cease, as it enables proper valuation and confidence in the removed CO_2. MRV relies on large amounts of systems-level data, supported by a suite of hardware and software components. These processes, and the technologies that support them, are vital to attracting finance and interested buyers of CDR credits. Improving MRV processes is not only vital to the integrity of the sector, but will also help reduce costs: companies have reported that MRV costs can sometimes represent 30-50% of the total CDR cost.

All CDR options involve multiple value chain steps, which sometimes require different MRV approaches in different locations. This elevates the need for interoperable datasets across, for example, the energy inputs to a DAC plant and the tracking of geological CO_2 storage (in terms of its plume migration, pressure buildup and overall integrity of the storage site). Some companies already offer digital MRV solutions to CDR project operators because advances in sensors, automation and digitalisation have enabled data to be collected and verified in real time. However, the most complex MRV challenges relate to technologies that depend on biomass cultivation or open systems such as enhanced rock weathering and alkalinity enhancement. For such systems it is impossible to monitor each leaf or grain of rock to assess the efficacy of carbon uptake, and there are uncertainties about the counterfactual baseline to be applied at a given time or at a specific location. Assumptions are necessary in some cases, but to ensure the long-term value of CDR credits, they must be based on reliable real-world scientific information. This information will become more reliable as each CDR technology accumulates more operational experience, but in the early stages of adoption it is scarce. From a public policy and customer confidence perspective, the proprietary nature of some of this data, as well as the limited number of companies operating CDR approaches (e.g. bio-oil), leaves a knowledge gap to be filled.

Status of selected technologies for monitoring, reporting and verification (MRV)

Technologies	MRV need	Status/action
Soil and water sampling and measurements	Measure rate of CO_2 storage absorption and quantity of CO_2 removal in open systems such as soil and water bodies (enhanced rock weathering, ocean alkalinity enhancement).	A wide suite of measurement techniques exist to follow each step of the weathering process from rock dispersion on land or in oceans to ultimate dissolution in oceans. Advanced technologies for measurements include cations/anions measurement of soil and pore water samples, radiogenic and metal stable isotopic measurements to fingerprint sources of cations in soil.
Modelling of biophysical and geochemical processes	Model rate of CO_2 storage absorption and quantity of CO_2 removal in open systems such as soil and water bodies (enhanced rock weathering, ocean alkalinity enhancement).	Models of biophysical and geochemical processes can help complement measurements when these are unpractical because of large spatial or temporal scale, particularly for downstream processes. While research is needed to improve understanding of the underlying science behind physical processes, such as weathering rates of different rocks, statistical models based on field data could also help increase robustness.
Underground storage remote monitoring	Monitor CO_2 or bio-oil fluid plume migration and detect leaks.	A range of well-established approaches used for decades in CO_2 storage monitoring (remote monitoring via 3D/4D seismic, electromagnetic surveys, microseismic measurements). Potential for hybrid approaches between repeat 3D seismic and electromagnetic surveys to improve accuracy and reduce costs.
Life cycle assessment	Measure project emissions for all approaches, with special attention to: • biomass production, processing and transport (bio-based CDR) • alkaline material collection, processing, and transport (surficial and ex-situ mineralisation) • inputs for the construction and operation of large-scale facilities (DAC, BECCS).	Well-established, with room for homogenisation of approaches, sharing of effective practices and digitalisation for live-tracking of supply chain emissions.
Remote sensing	Measure economic CO_2 leakage such as indirect land-use change from biomass production (bio-based CDR).	Use live remote sensing data to make economic leakage models more robust.

Information on projects and investments

Tracking CDR research results, project experiences and funding sources is key to understanding the current landscape of activities and identifying and quantifying future needs. To date there is no single repository for tracking such efforts across all CDR approaches and geographies. Knowledge gaps remain in relation to the funding sources, especially private funding, and how it is allocated between different CDR approaches. As such, it is challenging to get a full picture on the total level of funding support a given CDR technology is receiving. This information could provide valuable insight to policy makers who want to develop a portfolio of CDR solutions by pinpointing underfunded CDR technologies, estimating costs and identifying potential strategic advantages in CDR innovation.

Existing efforts include:

- The State of Carbon Dioxide Removal report. Updated annually by a team of researchers, this provides a significant amount of information on conventional and novel CDR approaches, based on their readiness levels, the scale at which they are currently deployed and their innovation and deployment needs.
- Mission Innovation's CDR Mission Global CDR Demonstration and Deployment Map. This provides updates on known pilots, demonstrations and deployment of DAC, biomass-based CDR and enhanced mineralisation projects.
- The IEA Clean Energy Technology Guide is an interactive framework that contains information for over 600 individual technology designs and components across the whole energy system. For each of these technologies, which include CDR technologies, it includes information on the level of maturity and a compilation of development and deployment plans, as well as cost and performance improvement targets and leading players in the field.

Priorities for reaching the next innovation stages

Innovation in CDR technologies can drive down costs, increase efficiencies, and promote durable, measurable and verifiable removals. There is an expectation of rapid growth in the market in the next decade, and countries at the forefront of these innovation efforts stand to benefit from investment and the economic gains of CDR deployment. Priorities for governments and other stakeholders in the near term relate to supporting larger-scale projects, facilitating access to testing facilities, managing market risk through procurement, and creating data repositories.

A global portfolio of pilot and demonstration projects to keep options open

With CDR approaches currently at a range of maturities and levels of substantiation, not all technologies will be able to reach million-tonne-scale capacity in the next decade. Developing a global portfolio of CDR pilot and demonstration projects is an effective way for governments to move forward the frontier for each option as quickly as possible, while identifying the most promising, and continuing to support innovation. For CDR, it will be important to balance the evolving needs of technologies at different stages.

Less mature pathways, such as some ocean-based and mineralisation technologies, require near-term focus on a range of pilot projects to prove their effectiveness and ability to scale up. For more mature pathways that have already benefited from such early support, such as some DAC and BECCS technologies, a focus on supporting demonstration projects that reduce the technological, financial and regulatory risks of commercial investments is essential.

While individual country support is important for domestic innovation ecosystems, collaboration between countries brings considerable efficiencies in the speed and costs of addressing key technical, policy and market challenges. Mission Innovation's CDR Mission is an important first step; Countries that have signed up are committed to fund at least one CDR project that removes 1 000 t CO_2 per year or more. It aims to share data and experiences on a subset of CDR pilot and demonstration projects through its CDR Launchpad initiative, but is currently limited to just seven countries.

Open-access facilities for testing CDR technologies

Access to cutting-edge laboratory and pilot-scale testing equipment can be difficult for early-stage companies to finance. Open-access facilities can be highly valuable for innovators because they reduce the times and risks associated with evaluating and certifying new designs, which is crucial for accessing finance. Such facilities are also sources of expertise and interaction among practitioners that help compress development times and reduce the errors in the "trial and error" process.

These types of facilities for CDR are currently in operation, albeit in a limited fashion. Canadian DAC developer Deep Sky plans to commission a testing ground for DAC technologies this year called the 'Alpha' project. It has received a USD 40 million grant from Breakthrough Energy, a philanthropic organisation, and will host up to ten companies to test, track and benchmark operational data to accelerate R&D of their DAC technologies. In the United States, the DAC Center at the National Energy Technology Laboratory provides accessible material-, module- and prototype-scale testing facilities and support for emerging technologies that have achieved proof-of-concept but have not reached full pilot scale. In addition, existing test centres for carbon capture technologies, such as the National Carbon Capture Center in the United States and the Technology Centre Mongstad in Norway, have recently expanded to include testing for DAC technologies.

These existing facilities are an excellent starting point to incorporate CDR technologies, but are currently limited to just DAC. Expanding open-access facilities to allow for testing of other CDR technologies is needed. Just one effort is currently underway: in the United States, the DoE recently issued USD 10 million specifically to testbed facilities that demonstrate the capacity to accommodate and enhance the testing of several CDR pathways.

A public sector push for CDR procurement

Above all, faster innovation in CDR technologies will be incentivised by a dependable market for credits. Such a market is also critical for large-scale demonstration and early commercial projects to attract finance. The emergence of a nascent voluntary market for purchasing millions of tonnes worth of credits for future delivery of high-quality removals – sometimes up to a decade in advance – has dramatically improved the ability of companies to scale up to large asset sizes in the past few years. Backing from the private sector has helped advance a few major projects to date, but voluntary carbon markets remain highly concentrated: around 60% of all novel CDR credits sold in the past 5 years come from just two BECCS projects, the majority of which came from one buyer, Microsoft. It is necessary for this market to expand to include more regions, projects and buyers.

Governments, through advance purchase commitments, are in a unique place to catalyse future demand across a diverse landscape of CDR technologies and companies, helping to crowd in additional private funding and de-risk initial investment. Indeed, such advance commitments by governments have been highly effective in injecting innovative solutions into the market, including in robotics and computing. The United States and Canada are now testing this approach for CDR.

Public procurement of CDR credits can bring several benefits:

- **Crowd in private capital**: Long-term (i.e. 10-year) purchases of CDR credits are important to attract the level of investment needed to build CDR projects, allowing emerging CDR companies to secure offtake deals and crowd in much-needed private capital. Initial government investment into procurement programmes can be relatively small, so long as growth remains steady over time and sufficient private capital is mobilised. In fact, just after the US DoE announced its Voluntary CDR Purchasing Challenge, Google pledged to match the DoE's commitment of at least USD 35 million in CDR credit purchases.

- **Increase transparency**: In running public procurement programmes, governments collect large amounts of data from CDR suppliers, from cost and performance data to key insights on MRV. Governments are well-placed to aggregate this information and make it publicly available to accelerate knowledge transfer.
- **Foster collaboration**: Public procurement can foster collaboration between public institutions, private companies and research organisations. Through these efforts, governments have better insight into how to classify high-quality removals.

Guiding principles for high-quality removals

The private sector and non-government organisations have to date been at the forefront of developing what qualifies as a high-quality removal, working to define CDR approaches based on their quality at the project-level. Examples include the Core Carbon Principles developed by the Integrity Council for the Voluntary Carbon Market and the Carbon Credit Quality Initiative's carbon credit scoring tool.

At the same time, some governments are working to establish related criteria for high-quality removals. For example, the voluntary EU Carbon Removal Certification Framework defines fundamental principles for certification bodies to monitor and verify removals generated in the European Union, and the United Kingdom is developing MRV methodologies for a GHG removal standard for domestic projects. Separately, at the international level, the Intergovernmental Panel on Climate Change (IPCC) is developing a methodology report to outline a framework for including technology-based CDR methods in national GHG inventories, which is currently planned for release in 2027 – though the focus of the IPCC guidelines will be on quantifying removals, rather than assessing their quality.

Whether it is for voluntary or compliance markets, it will be important to come to a common understanding of what constitutes a high-quality removal and establish a broad agreement on the important factors to consider – currently there is no clear consensus among scientists and policy makers. Such considerations may include:

- Durability or permanence: what is the minimum threshold of storage durability that should be included? Existing policies by governments and voluntary standard-setters have various minimum thresholds for storage, from 100 years (United States and Puro.earth) to centuries (European Union).
- Quantification and verification: does the CDR activity result in net negative CO_2 emissions when taking life cycle emissions into account? Is there a framework or LCA methodology for verifying emissions removals? What are the LCA boundaries and assumptions of upstream emissions?

- Additionality: the CDR activity would not otherwise occur and results in net carbon removal compared to a baseline scenario in the absence of investment.
- Social and environmental considerations: does the activity minimise social harms and impacts to the environment?

A two-way flow of project-level data and research to improve monitoring, reporting and verification processes and technologies

As more projects become operational and collect real-world data, there is a growing need to align this project-level data with scientific research, and vice versa, underpinned by a two-way flow of data and practical experience.

With advances in automation and digitalisation, companies are able to collect information about a project that could provide baseline-level data to inform the scientific community's modelling of CDR approaches and their effects. These better-informed research efforts, along with operational cost data from projects, can then, in turn, improve lifecycle assessments, improve MRV processes and reduce costs, and identify resource availability and needs of CDR approaches. For example, project-level data from geological storage sites on CO_2 saturations and mass balances can help calibrate and validate simulation models that are used to select CO_2 storage sites and forecast CO_2 plume migration.

Practical examples of this collaboration are starting to emerge. Climeworks developed an MRV methodology for DAC in partnership with CarbFix and DNV, and is now partnering with the Lawrence Livermore National Laboratory in the United States, providing real-world project and technical information to national laboratory teams who will then translate this experience to test an overarching framework for MRV. Another example is Vesta, which is making its ocean alkalinity enhancement field trial results available to the public.

Governments are uniquely positioned to be arbitrators of this data and should work together with these communities in a coalition of data- and knowledge-sharing. Governments should tie public funding to requirements to share such information in consistent formats with regulators and this coalition.

Annexes

Annex A: Stakeholder survey questions

The survey to support this report was anonymous. The questions were the following:

In which country are you based?

For which organisation do you work?

Are you a member of any of the following international initiatives?

"IEA Technology Collaboration Programme; Mission Innovation Mission; Mission Innovation Collaborative Initiative; UNFCCC TEC or CTCN; Clean Energy Ministerial Initiative or Campaign; None of the above; Other."

Do you primarily work in a particular technology area?

"No, I work across various technologies; Energy efficiency; Energy storage and batteries; Hydrogen and fuel cells; Decarbonisation of heavy industry; Nuclear; Carbon capture, utilisation and storage (CCUS) and Carbon dioxide removal (CDR); Critical minerals; Power and grids; Renewables; Transport; Other."

How do you judge the current rate of progress with energy technology innovation compared with the decade from 2010 to 2020?

"Things are better than ever; Impressive progress despite poor policy support; Plenty of money but too few real-world impacts; Efforts are too concentrated in a small number of places; Efforts are too diversified and no technology receives enough support; The rate of progress is about the same as in 2015; It's slowing down too much; I cannot judge the progress."

What is your expectation for energy technology innovation in the next 12 months compared with the previous 12 months?

"Very positive; Positive; Neutral; Negative; Very negative."

Which energy technology do you think took the most exciting step towards commercialisation in 2024?

Which energy technology project (or company) do you think reported the most exciting results or achievements in 2024?

"More specifically, what type of results or achievements were these? (The attraction of a notable funding package; recognition with an award; the award of an offtake contract; successful operation of a pilot or demo installation; evidence of a technical advance (performance improvement or cost reduction compared to competitors); announcement of a project, consortium or joint venture."

Which area of energy technology innovation do you expect to make exciting news in the next couple of years?

Is there a technology area for which you are concerned that progress is moving too slowly?

Which government policy measure provides an example of good practice in your opinion?

Which lab, project or company is making impressive progress with technology development in an emerging or developing economy?

In your area of technology and geographical expertise, is there a type of capital for which innovators lack access and governments could do more to make it accessible?

List of energy technology areas provided in the State of Energy Innovation – Stakeholder survey

Energy efficiency
- Building design, envelope and passive systems
- Building controls (incl. BEMS)
- Heating (space, water, industrial)
- Cooling
- Industrial processes
- Data centre energy use
- Lighting

Energy storage and batteries
- Thermal storage
- Mechanical storage (e.g. flywheel, compressed air)
- Battery recycling and reuse
- Battery maker: Li-ion
- Battery maker: solid state
- Battery maker: redox flow
- Battery maker: other batteries
- Battery management system

New approaches for heavy industry
- Near-zero emissions steel
- Near-zero emissions cement and concrete
- Industrial heat
- Alternative chemicals feedstocks (e.g. biomass, CO_2)

Hydrogen and fuel cells
- H_2 production: electrolysis
- H_2 production: with CCUS
- H_2 production: natural hydrogen
- H_2 production: other
- H_2-based fuels (e.g. synthetic fuel, NH_3)
- H_2 storage and infrastructure
- H_2 fuel cells

Nuclear, CCUS, CDR, methane, critical minerals, energy access
- Nuclear fission
- Nuclear fusion
- Point-source capture (incl. BECC)
- Direct air capture
- Geological CO_2 storage
- Mineralisation and enhanced weathering
- CO_2 transport
- Methane management
- Critical minerals
- Energy access

Power and grids
- Physical electricity grid technologies
- Digital grid management (incl. VPP, DERMS)
- Emerging power generation technologies (e.g. waste heat to power, NH_3-based)

Renewables
- Geothermal
- Hydro
- Ocean
- Solar PV
- Solar thermal
- Wind
- Bioenergy (e.g. biogas, liquid, biorefining, solid, feedstock)

Transport
- Aviation
- Electric vehicles
- EV charging
- H_2-powered transport
- Shipping and boats
- Rail

Annex B: Currency conversions

Throughout the report, monetary values are reported in USD. Analyses of research and development spending, venture capital investment and demonstration project value are presented in real terms, inflated to USD (2024) and converted at market exchange rates. Monetary values associated with individual project or policy announcements and budgets have been converted from national currency to USD using the average market exchange rate of the year in question.

Annex C: Abbreviations and acronyms

AI	Artificial intelligence
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CDR	Carbon dioxide removal
CERT	Committee on Energy Research and Technology
CfD	Contract for difference
CHP	Combined heat and power
CoP	Coefficient of performance
CO_2	Carbon dioxide
CSP	Concentrated solar power
CVC	Corporate venture capital
BECCS	Bioenergy with carbon capture and storage
DAC	Direct air capture
DLE	Direct lithium extraction
DRI	Direct reduced iron
EIB	European Investment Bank
EMDE	Emerging market and developing economy
EoL	End-of-life
ESA	Electro swing adsorption
EV	Electric vehicle
GHG	Greenhouse gases
H_2	Hydrogen
IPCC	Intergovernmental Panel on Climate Change
IPF	International patent families
ISGAN	International Smart Grid Action Network
LCA	Life cycle assessment
LCE	Lithium carbonate equivalent
LFP	Lithium iron phosphate
LHM	Lithium hydroxide monohydrate
LNMO	Lithium nickel manganese oxide
LNO	Lithium nickel oxide
LMFP	Lithium manganese iron phosphate
LPG	Liquefied petroleum gas
MI	Mission Innovation
MOF	metal organic framework
MoU	memorandum of understanding
MRV	monitoring, reporting and verification
NCA	Lithium nickel aluminium cobalt oxide
NMC	Lithium nickel manganese cobalt
NMCA	Lithium nickel manganese cobalt aluminium oxide
N_2O	Nitrous oxide
NO_x	Nitrogen oxides

PEM	Proton exchange membrane
PV	Photovoltaic
R&D	Research and development
RD&D	Research, development and demonstration
RoP	Rate of Penetration
SHC	Solar heating and cooling
SMR	Small modular reactor
STEPS	Stated Policies Scenario
TCP	Technology Collaboration Programmes
TRL	Technology readiness level
VC	Venture capital

Annex D: Glossary

bar	bar
g	gramme
GJ	gigajoule
Gt	gigatonne
Gt CO_2	gigatonne of carbon dioxide
Gt CO_2-eq	gigatonne of carbon dioxide equivalent
GW	gigawatt
GWh	gigawatt hours
GWh/yr	gigawatt hours per year
GWP	global warming potential
hr	hour
kt	kilotonne
kV	kilovolt
kW	kilowatt
Mt	million tonnes
Mt CO_2	million tonnes of carbon dioxide
Mt/yr	million tonnes per year
MW	megawatt
MWh	megawatt hour
MWth	megawatt thermal
Nm^3	normal cubic metre
W	watt
sqm	square metre
t	tonne
USD	United States dollars

See the IEA glossary for a further explanation of many of the terms used in this report.

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