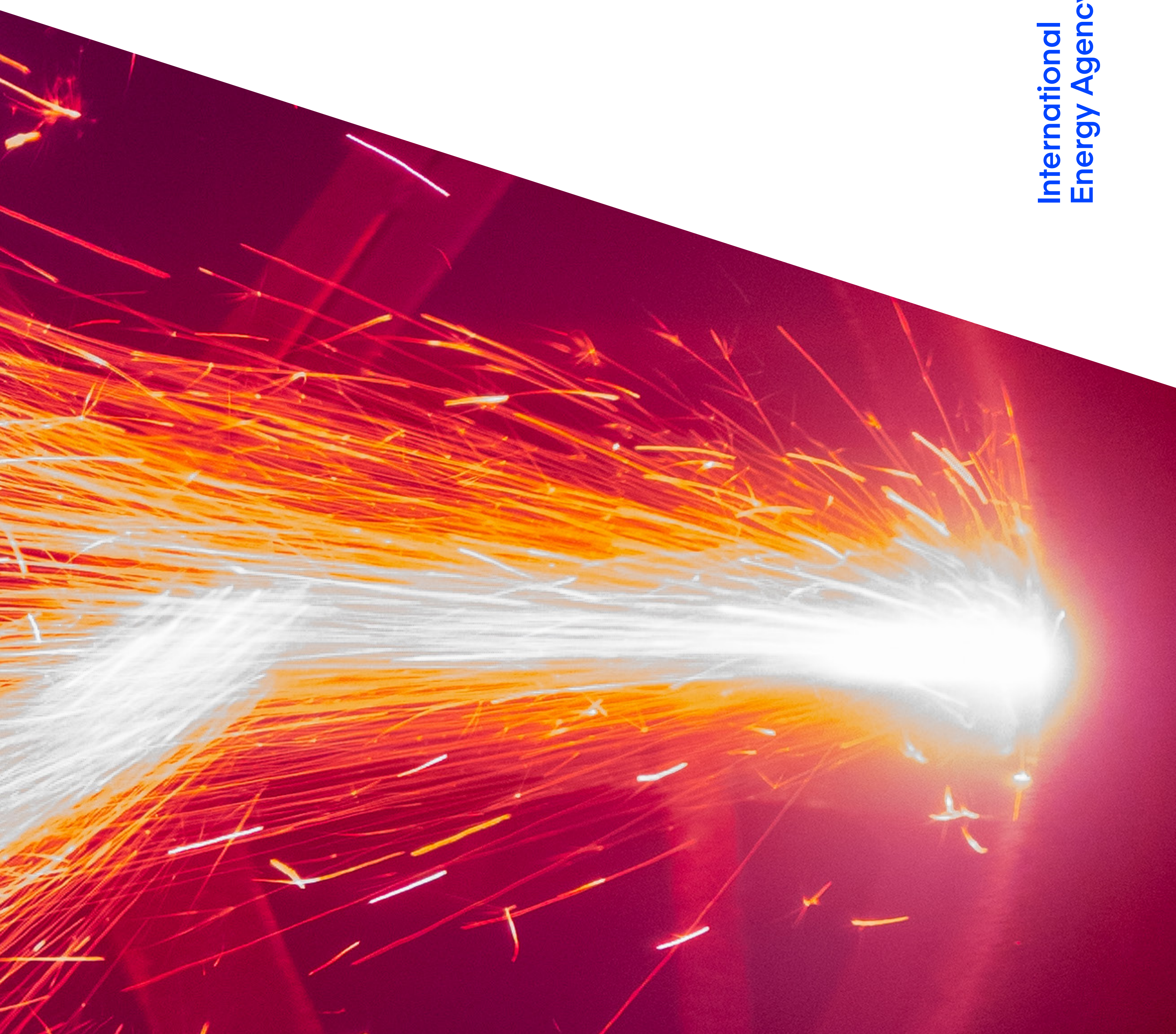
The State of Energy Innovation 2026

International Energy Agency



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Abstract

The second edition of *The State of Energy Innovation* turns the spotlight on the technologies, policies and funders at the forefront of energy technology development. It provides a comprehensive assessment of recent progress and emerging challenges in energy technology innovation, drawing on over 150 innovation highlights from 2025 and a survey of practitioners across more than 40 countries. It analyses trends in public and corporate R&D spending, venture capital flows, patenting and policy, as well as providing an update on progress towards the 18 IEA Races to First in energy innovation. This data-driven approach informs policy makers, industry and other stakeholders on the state of energy innovation worldwide and the importance of sustaining innovation momentum over the long term.

The report finds that the context for energy innovation is tilting towards competitiveness and security. Many of the innovation-relevant policies launched in 2025 promote technological strength for economic competitiveness and energy security. The share of all patents that are related to energy is growing, and over 320 new energy start-ups raised their first funding in 2025. These are signals of an active ecosystem but innovators depend on a predictable funding and policy framework. The report shows that the value of spending on energy innovation can be seen in market outcomes, with public energy innovation support behind some recent, major steps forward in the energy sector. The report includes several timely policy recommendations and in-depth chapters on two dynamic fields, namely technologies to enhance electricity grid resilience and advance fusion energy.

Acknowledgements, contributors and credits

The *State of Energy Innovation 2026* was prepared by the Energy Technology Policy (ETP) Division of the Directorate of Sustainability, Technology and Outlooks (STO) of the International Energy Agency (IEA). The project was directed by **Timur Gül**, IEA Chief Energy Technology Officer.

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The development of this report also benefitted from reviews from IEA senior management and other IEA colleagues: Laura Cozzi, Keisuke Sadamori, Dan Dorner, Tim Gould, Zubin Postwalla, Roberta Quadrelli, Rebecca Schulz, Cecilia Tam.

Per-Anders Widell and Charlotte Bracke provided essential support throughout the process. Lizzie Sayer edited the manuscript.

Thanks also to Maria Ahmad, Curtis Brainard, Poeli Bojorquez, Jon Custer, Astrid Dumond, Merve Erdil, Grace Gordon, Josh Hammond, Jethro Mullen, Irina Paun, Isabelle Nonain-Semelin, Sam Tarling, Clara Vallois, Lucile Wall and Wonjik Yang of the Communications and Digital Office.

Special thanks go to Yann Ménière and his team at the European Patent Office for patent-related data. The work is also indebted to the more than 270 respondents to the survey that was conducted in support of the report.

The work could not have been achieved without the financial support provided by Government of Canada, the Government of Germany and the Government of Japan. Several sections benefited from the financial assistance of the European Union as part of its funding of the Clean Energy Transitions in Emerging Economies programme (CETEE-2) within the Clean Energy Transitions Programme, the IEA's flagship initiative to transform the world's energy system to achieve a secure and sustainable future for all.

Peer reviewers provided essential feedback to improve the quality of the report. They include: Putra Adhiguna (Shift Institute), Hugh Barlow (Global CCS Institute), Harmeet Bawa (Hitachi Energy), Jonas Bergqvist (Almi Invest GreenTech AB), Elena Bou (InnoEnergy), Chiara Bustreo (Environmental, Safety and Economic Aspects of Fusion Power TCP), Jose Caceres Blundi (GE Vernova), Brendan Cahill (Sustainable Energy Authority of Ireland), Diane Cameron (Nuclear Energy Agency), Lucy Corcoran (Department of Climate, Energy and the Environment, Ireland), Beatriz Crisóstomo (Iberdrola), Luis Cunha (E-Redes), Greg De Temmerman (Techleap), Greg Degen (Commonwealth Fusion Systems), Olivier Demaret (SPF. Economie, Belgium), Luca Dona (IONATE), Francesca Ferrazza (ENI), Cody Finke (Brimstone), Jason (Gadoury (Natural Resources Canada), Fernando Galindo Rueda (OECD), Geoffroy Gauthier (Energy Storage TCP), Brian Grierson (General Atomics), Bert Gysen (Energy Storage TCP), Caroline Haglund Stignor (Heat Pumping Technologies TCP), Tyler Hamilton (MaRS Discovery District), Taku (Hasegawa (Kawasaki Heavy Industries), Daniel Hermann (Ministry of Energy, Hungary), Nabil Hitti (Nationalgrid Ventures), Andrew Holland (Fusion Industry Association), Birte Holst Jørgensen (Technical University of Denmark), Peter Horvath (European Commission, DG Energy), Andrej Jentsch (District Heating and Cooling TCP), Paul Kaajik (Agence de la transition écologique, France), Michael Keenan (OECD), David Kingham (Tokamak Energy), Torgeir Knutsen (Ministry of Energy, Norway), Alar Konist (Fluidized Bed Conversion TCP), Atsushi Kurosawa (Institute of Applied Energy, Japan), Eya Li (International Council on Clean Transportation), Paul Luchese (Hydrogen TCP), Lisa Lundmark (Swedish Energy Agency), David Maisonnier (Fusion Power Coordinating Committee), Juan Bautista Martinez Amiguetti (Ministry for the Ecological Transitions, Spain), Luciano Martini (ISGAN TCP), Vincent Minier (Schneider Electric), Sabine Mitter (Federal Ministry of Innovation, Mobility and Infrastructure, Austria), Johanna Mossberg (Industrial Energy-Related Technology Systems TCP), Nobuto Nakanishi (Panasonic Energy), Michele de Nigris (Ricerca sul Sistema Energetico), Brian O'Gallachoir (ETSAP TCP), Peta Olesen (Department of Climate Change, Energy, the Environment and Water, Australia), Dimitri Pescia (Agora Energiewende), Thomas Sun Perdersen (Type One Energy), Marcia Poletti (Octopus Energy), Martin Pihl Andersen (Danish Technological Institute), Teresa Ponce de Leao (Laboratório Nacional de Energia e Geologia, Portugal), Sandiswa Qayi (AET Africa), Olga Rataj (UNIDO), Joonas Rauramo (Coolbrook), Isabella Reid (Department for Energy Security and Net Zero, United Kingdom), David Reiner (University of Cambridge), Stephane Renz (Heat Pumping Technologies TCP), Timo Ritonummi (Ministry of Economic Affairs and Employment, Finland), Arlette Rivera Diaz (Ministry of Energy, Mexico), Nicola Rossi (Enel), Ambuj Sagar (Indian Institute of Technology, Delhi), Kentaro Sakaguchi (Mizuho), Toshiyuki Sakamoto (Institute of Energy Economics Japan), Michael Segal (Commonwealth Fusion Systems), Kerrie Sheehan (Sustainable Energy Authority of Ireland), Matthijs Soede (European Commission, DG R&I), Meli Stylianou (Energy in Buildings and Communities TCP), Peter Taylor (University of Leeds), Yoshihisa Tsukamoto (Toyota), Fabby Tumiwa (Institute for Essential Services Reform), Ulderico Ulissi (CATL), Noé Van Hust (Independent), Tom Veli (LCP Delta), Jaap van Kampen (Siemens), Michael Weismiller (Electric Vehicles TCP), Robin Wiltshire (District Heating and Cooling TCP), Robert Wolf (Stellarators and Heliotrons TCP), Christoph Wolter (Danish Energy Agency), Markus Wråke (Energiforsk), Yican Wu (Nuclear Technology of Fusion Reactors TCP), Kasumi Yasukawa (Geothermal TCP) and Benjamin White (Advanced Materials for Transportation TCP).

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Executive summary

Successful energy innovations can have outsize economic and social outcomes, impacting industrial competitiveness, trade, environmental health, infrastructure investment and security. The second edition of the *State of Energy Innovation* turns the spotlight on the technologies, policies and funders at the forefront of this process. Today, the global markets for energy technologies such as batteries, transformers, turbines, motors and heat exchangers are worth trillions of dollars. With spending on energy representing as much as 10% of global GDP, innovation that reduces energy supply costs can transform a country's comparative advantage. As a result, the energy sector is innovation-intensive: one in ten patents is related to energy – more than for chemicals, pharmaceuticals or transport.

Today, the context for energy innovation tilts towards competitiveness and security. In our survey of experts and practitioners, 80% of respondents placed energy security among the top three drivers of energy innovation in 2025, ahead of affordability, GHG emissions and national economic performance. Many of the innovation-relevant policies announced in 2025, including the US Genesis Mission and the proposed EU Competitiveness Fund, promote technological strength for economic competitiveness and energy security. This may boost technologies that support critical minerals supplies, nuclear, power grids, and domestic energy resources.

The value of public spending on energy innovation can be seen in market outcomes

Public energy innovation support is behind some recent, major steps forward in the energy sector, and pays off for decades into the future. Lower project costs and new designs have brought investment to floating liquefied natural gas (FLNG), which is expected to deliver more than one-eighth of global LNG capacity by 2030, from zero just 10 years ago. Initial FLNG design and testing was funded by European governments in the late 1990s, and the European Union and Japanese government shared funding risks with the private sector on the first major project. Similarly, lithium-ion battery research was initially publicly funded in the 1970s, and the first patent was funded by the UK Government in 1981, before policy support fostered markets that drove further improvements. In the absence of private sector capital for next-generation geothermal development – a long-term project with high risks that is now starting to translate into major investments – governments funded nearly all the initial work from the 1970s to the 2010s.

Cost-benefit evaluations typically show that the economic benefits of public energy R&D are far greater – even a hundredfold larger – than their costs. The most complete retrospective evaluations of this kind followed several multi-decade US programmes up to 2015. These programmes generated benefits to the US economy at least three times greater than their costs, including fuel expenditure savings, lower prices for energy equipment and higher sales of energy products. Examples such as R&D for geothermal, wind and buildings efficiency resulted in several hundreds of dollars in benefits for every dollar of cost. The impacts of many of these initial investments are likely to have grown since these analyses were conducted, as markets for the resulting products expanded, and "spillovers" to adjacent areas spurred new ideas and inventions around the world.

Energy innovation strengths and industrial strengths can reinforce one another. Analysis of different countries' revealed technology advantages (RTA)[1] in energy technologies shows that the world's largest fossil fuel producers now have the highest specialisation in fossil fuel technologies, and countries that invested early in wind power now have the highest advantages in wind energy patenting. However, technical specialisation does not automatically translate into industrial competitiveness; it requires close attention to manufacturing advantages, and strategic trade or knowledge partnerships.

A dynamic time for energy innovation

Across a range of indicators, extensive innovation activity is visible around the world. We identify over 150 significant energy innovation highlights in 2025, in areas including solid-state air conditioning, perovskite solar, fusion energy, sodium-ion batteries and next-generation geothermal. These advances led to 50 upgrades of technology readiness levels for emerging energy technologies followed by the IEA. Among the IEA Races to First that track progress towards 18 energy breakthroughs, frontrunner projects propelled 3 races into a higher phase. The report also identifies more than 80 new energy innovation policies introduced in 2025, as well as over 60 new initiatives issued under existing policies across 32 countries and jurisdictions. According to the latest patent data, energy occupied a higher share of all patents in 2023 than in the year before. Over 320 new energy start-ups raised their first funding in 2025, a signal of an active ecosystem.

However, uncertainty abounds as markets for some clean energy technologies weakened. For example, project delays and cancellations reduced expectations for the deployment of low-emissions hydrogen this decade. The IEA's renewables deployment forecast for 2030 was downgraded by 5% in 2025 in response to policy and regulatory changes. Several major first-of-a-kind energy

[1] This indicator reflects how specialised a country is in a given technology. It is calculated as the share of a country in patents in a particular technology divided by the country's share in all patents. An RTA greater than 1 indicates specialisation.

technology projects under construction, in areas such as near-zero emissions steel and direct air capture, required emergency funding packages or job cuts to cope with higher costs and policy uncertainty. The US federal energy R&D budget dipped by 8% in 2025 and some budgeted spending was paused or cancelled as research priorities came under review, leaving some researchers and project developers short of funds or pivoting towards different markets.

Funding shows signs of being in transition

After years of growth, energy innovation funding appears to be entering a phase marked by slower growth and shifting priorities. Public energy R&D spending globally in 2024 dropped from its recent high point in 2023, and our estimate for 2025 is down a further 2% to USD 55 billion. This is partly due to large recent commitments to demonstration projects from the 2023 EU budget, but also reflects cuts in the US federal budget. In total, public energy R&D spending in IEA Member countries stands at around 0.05% of GDP, far lower than the 0.1% seen in the aftermath of the 1970s oil shocks as countries sought to diversify their energy systems, though there are significant regional variations. At 1%, growth in corporate energy R&D was slower than in any year since 2015 (except for pandemic-hit 2020). It stood at USD 160 billion in 2024, the last year for which data is available. VC investments in energy technology start-ups shrank for the third year straight in 2025, to USD 27 billion.

There is no single reason for the decline in energy VC funding since 2022. Higher interest rates and an uncertain macroeconomic environment were initially leading factors. They encouraged investors to make fewer investments and to wait longer before investing, which cut larger, late-stage deals. VC markets have now partly rebounded but, in 2025, energy start-ups faced stiff competition for capital from AI firms: the share of VC funding for AI rose to almost 30% in 2025, while the share of energy shrank, and large non-specialist VC funds shifted focus from energy to AI. The post-peak decline in electric mobility VC is another factor – without this, energy VC in total would have been nearly flat.

New growth areas for energy VC are taking shape, and they reflect shifting priorities. Seven technology areas – carbon dioxide removal, critical minerals, next-generation geothermal, low-emissions industrial production, aerospace, nuclear fission and fusion energy – have offset most of the decline in electric mobility VC funding since 2021. From 2015-2019, these seven areas represented less than 5% of total energy VC funding (of which aviation accounted for half); in 2025, they represented one-third of the total funding.

The share of energy patenting going to batteries is unprecedented

If patenting is a leading indicator of technological change, battery innovation will remain a disruptive force in the energy sector and beyond. The share of energy patenting represented by energy storage is rising, reaching 40% in 2023. Based on preliminary data, this is set to grow further in 2024 and 2025. Our analysis suggests that no other energy technology has ever commanded such a dominant share, reflecting the strategic importance of batteries for modern energy security, industrial policy and grid infrastructure, as power demand surges globally. China, Korea and Japan remain the leading sources of lithium-ion battery patents, though their relative contributions have shifted. In 2010, Japan filed half of all cathode-material patents; by 2022 its share had fallen to below 10%. Over the same period, China's share rose from 4% to almost 40%.

Mature technology areas do not stand still. Since 2010, patenting for crystalline silicon PV has fallen while patenting for solar perovskite has grown, and it now accounts for over 70% of all solar cell patents. China leads perovskite patenting globally, followed by Korea and Japan. In 2025, perovskite reached several innovation milestones, including the world's first 33% efficiency solar cell at marketable dimensions. While it is not expected to displace crystalline PV, it could expand the total market for PV.

Regional trends are diverging

China's pursuit of innovation-led growth is seen in its funding, patenting and technology milestones. Higher spending on energy R&D by Chinese companies explains almost all the growth in corporate energy R&D globally over the past decade, and they now account for 60% of corporate R&D for the energy supply and infrastructure sectors. China's public energy R&D spending is on par with Europe's, but its patenting is now far larger: Chinese inventors made double the number of applications for international energy patents in 2023 compared with 2020, reaching twice the level of the United States, Japan or Europe. Patenting is especially focused on energy storage and industrial energy efficiency. China achieved multiple innovation milestones in 2025, including extending the record for perovskite solar tandem cell efficiency, demonstrating the first kilowatt-scale solid-state air conditioning, and planning the first 50 MW floating wind turbine.

Europe has steadily risen closer to 0.1% of GDP spent on energy R&D. Revised EU data for public R&D spending show Europe pulling away from the United States and Japan in recent years, and reaching 0.08% of GDP. Energy efficiency and nuclear technologies represented over half of the USD 19 billion of European public energy R&D spending in 2024. The region's energy innovation ecosystem is also becoming more dynamic: European start-ups accounted for 25% of global energy VC in 2025, compared with 15% five years before, and Europe was home to more than 40% of energy start-ups raising their first funding round. However, energy technology patenting in major European countries has dipped, according to the latest data, and European start-ups typically raise less than their US counterparts. Nonetheless, a large share of the innovation highlights identified for this report took place in Europe, including for fusion energy, underground hydrogen storage, industrial electrification, power grid stabilisation, CO_2 storage, synthetic fuels and methane detection. Of the projects in the more advanced phases of the IEA Races to First, 40% are in Europe.

The United States continues to be an energy innovation powerhouse. A reorientation of energy R&D priorities is underway, while many of the underlying strengths of the US energy innovation ecosystem persist. US energy innovation spending is more equally spread between government, corporations and VC investors than in other countries. Nearly 50% of global energy VC in 2025 was raised by US start-ups, a higher share than in 2024, largely funded by US-based investors. US energy technology patenting is also distributed across multiple technology areas. Among the US innovation highlights in 2025 were the largest solid-state thermal battery, more reliable geothermal drilling, improvements to lithium-ion batteries with reduced nickel and cobalt, and investments in novel aviation designs. Of the projects in the more advanced phases of the IEA Races to First, 20% are in the United States.

Japan's innovators are racing to stay ahead in batteries. Japan's energy patenting is heavily skewed towards batteries, including advanced chemistries. Japan has the highest RTA in batteries of any major economy, just ahead of Korea, whose battery RTA has declined since 2020. A Japanese company is among the leaders in the IEA Race to First for a solid-state battery car. After China, Japan patents more in low-carbon energy areas than any other country and the whole of Europe. Thanks to stable spending, including the R&D component of the USD 75 billion Green Transformation fund, Japan is well-placed in emerging areas, such as solar perovskite, fusion, and hydrogen-based fuels – a Japanese company completed the first full-scale testing of an ammonia ship engine in 2025.

Fusion and grid technologies show the wide spectrum of energy innovation challenges

Future electricity grid resilience can be ensured with technology, thanks to recent, farsighted R&D, especially from governments. Recent major blackouts are a warning that grids must be more resilient to events including natural hazards and unplanned changes in power supplies. If not addressed, these challenges will undermine economic growth, national security and quality of life for citizens around the world. Several cutting-edge technologies – like grid-forming inverters, solid-state transformers and long-duration energy storage – have been developed in government programmes in recent years and are now proven solutions, alongside market and regulatory reforms. However, unless governments can address systemic regulatory disincentives to the deployment of innovative technologies, they will fail to deliver their potential.

Gigawatts of fusion power remain some time away, but long-standing international co-operation in public R&D has brought it to the cusp of demonstration. Fifty years after the IEA began supporting international co-operation on fusion, major experimental milestones were reached in 2025 in government-funded facilities in China, France, Germany, the United Kingdom and the United States, by consortia involving over 30 other countries. These advances have raised hope of a radically different way to power a future economy in the age of electricity, and there is stronger interest from funders – fusion start-ups have raised USD 10 billion since 2020, over 5% of all energy VC funding, and many are also funded by multiple governments. However, a clear-sighted view of the challenges is necessary: despite recent attention to engineering the first integrated fusion energy plants, the fuel cycle and materials are still not ready for scale-up. This introduces a possible tension between considering fusion energy as a race for first-mover advantages, and the benefits of cross-border collaboration that can continue to enable rapid scientific progress. There will be value in funding ways to share the daunting costs and construction hurdles that could limit the pace of deployment in any single region.

Even as the aims of energy innovation policy diverge, the policy priorities remain the same

The findings of this report highlight the continued importance of continuous, converted policy action. In particular, they show the relevance of public spending on energy R&D and early commercial projects for a range of key policy goals, especially as private finance has become scarcer. The enduring potential of innovation holds significant value for long-established and breakthrough areas.

The many energy innovation policies that have been released or updated in the past year reflect progress against the ten priorities for policy makers identified in last year's edition of this report, but also more policy volatility in some regions. The full set of ten priorities remains a good near-term guide to providing policy stability and realising long-term impact. However, against a backdrop of uncertainty and competing demands for the attention of governments and investors, we highlight three areas of action that have special relevance for the coming year.

- **Target synergies between competitiveness, resilience & energy technology**. Identifying how energy-related challenges are holding back domestic investment in key industries and supporting a range of potential solutions will be important.

Another approach could be to pinpoint comparative strengths to ensure that innovators can excel in international markets and reinvest in domestic value chains. In a more fragmented world, innovation support must consider technologies up and down the supply chain from major energy innovation projects.

- **Tailor funding to address current financial weaknesses**. Continuous access to funds across all innovation stages must be ensured if energy innovation is to reliably address policy goals. For example, if private funds for scale-up are gravitating to AI projects, the public sector can intervene temporarily in the interest of long-term outcomes. If VC investors continue to be wary of giving early-stage energy technologies a chance, innovators may benefit from finance, demand signals or fiscal incentives to draw in private capital. Reaching 0.1% of GDP on public energy R&D is achievable with a range of tools, tailored to the risks of failure that are inherent to innovation.
- **Bolster partnerships, networks and matchmaking**. The connective tissue of the innovation ecosystem should be strengthened, both internationally and across sectors. At a time when some traditional linkages are fraying, strong networks are crucially important for maintaining speed and efficiency. Innovation depends on the ready exchange of knowledge, skills and capital. The role of agencies and initiatives that connect researchers, entrepreneurs and first-of-a-kind project developers with expertise, risk-tolerant customers and funding will be especially important this year.

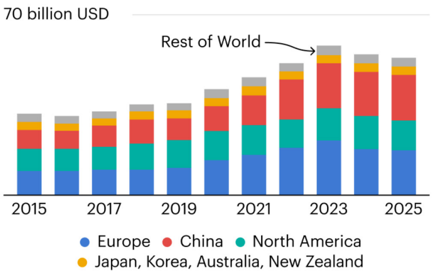
State of Energy Innovation 2026

The State of Energy Innovation turns the spotlight on the technologies, policies and funders at the forefront of energy technology development, using a data-driven approach to assess recent progress and emerging challenges.

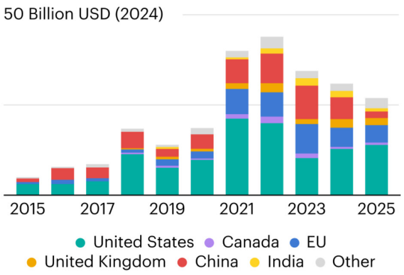
After years of growth, energy innovation funding appears to be entering a phase marked by slower growth and shifting priorities

Corporate energy R&D spending grew by just **1% in 2024,** the lowest rate since 2015

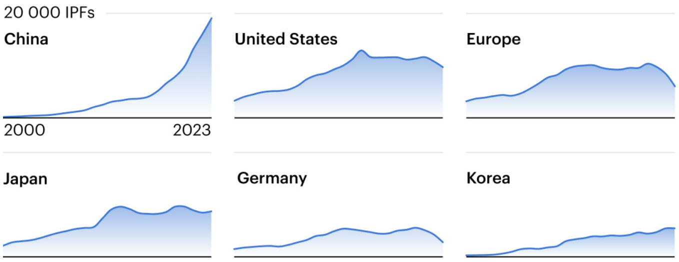
Government spending on energy R&D, 2015-2025



Venture capital investment in energy start-ups, by region, 2015-2025



Energy patenting of the five countries with the most applications, plus Europe, 2015-2023

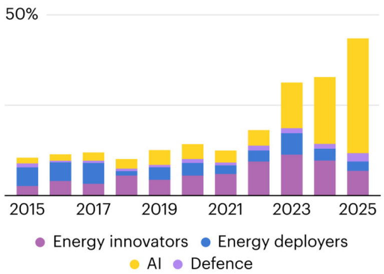


"Among the IEA Races to First that track progress towards 18 energy breakthroughs, frontrunner projects propelled 3 races into a higher phase"

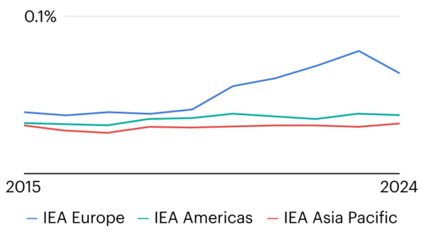
Phase 2 ^ Phase 1	**Phase 2** ^ Phase 1	**Phase 3** ^ Phase 2
The first solid-state cooled building	The first large-scale near-zero emissions cement	First freight ship powered by a carbon-free fuel

If patenting is a leading indicator of technological change, battery innovation will remain a disruptive force in the energy sector and beyond.

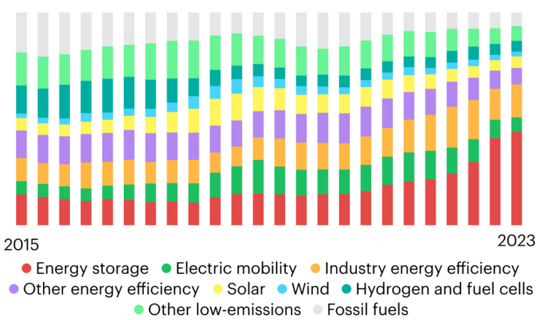
Total VC and shares of energy, AI, defence



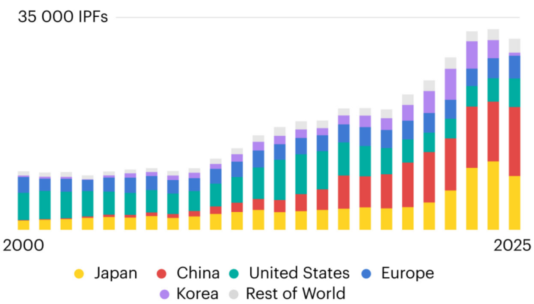
IEA Members' public energy R&D spending as a share of GDP, by region, 2015-2024



Energy patents by technology in the world, 2000-2023



Critical minerals patenting growth



Across a range of indicators, extensive energy innovation activity is visible around the world. However, uncertainty abounds.

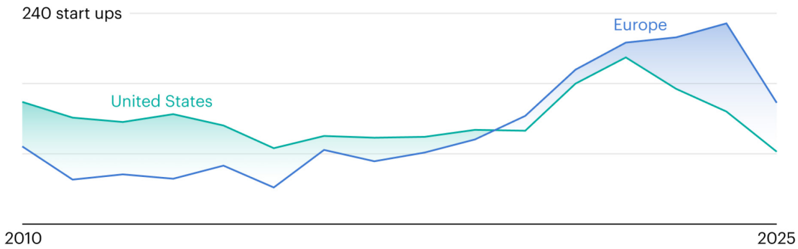
"This report presents a selection of policy updates from 2025 covering..."

32 *Countries and jurisdictions*

80 *New policies*

80 *Examples of actions taken under existing policies*

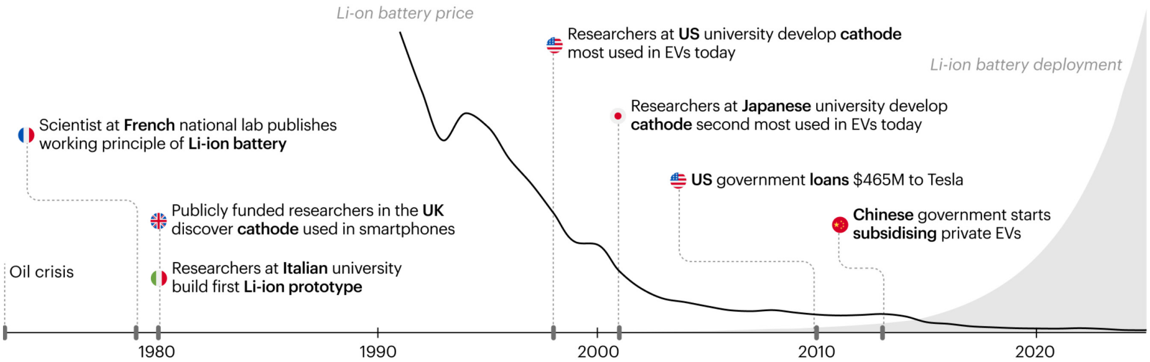
Number of energy start-ups raising their first equity per year in the United States and Europe, 2015-2025



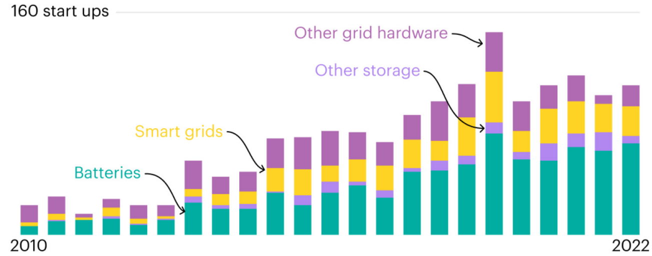
According to our survey, energy innovation is motivated by multiple strategic objectives

Public energy innovation support is behind some recent, major steps forward in the energy sector, and pays off for decades into the future.

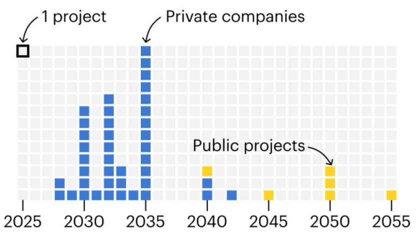
Global deployment, price, and key publicly funded milestones for lithium-ion batteries, 1973-2025



Number of grid technology start-ups founded, 2010-2022



Announced start years for electricity-generating fusion plants, 2025-2055



Three areas of action that have special relevance for the coming year

1 **Make strategic decisions**
Synergies between competitiveness, resilience and energy technology should be identified.

2 **Close funding gaps**
Continuous access to funds across all innovation stages must be ensured. A range of instruments are available.

3 **Establish partnerships**
The connective tissue of the innovation ecosystem needs strengthening, internationally and across sectors.

Introduction

Energy innovation is a long-term commitment, yet the prospects for a new energy technology can transform much more rapidly, as in the past year. Several macro-level developments have reordered the drivers for developing and deploying innovative energy products. Many governments have elevated energy security, supply chain resilience, domestic leadership in artificial intelligence (AI), industrial production and affordability among their energy and economic policy priorities. Markets are responding with stronger demand signals in these areas, but the effects will vary between technology fields, leading in some cases to an acceleration of an innovation process that typically plays out over years or even decades in the energy sector, and to greater risks in others. Addressing climate change remains a key driver for innovation but is now more conditional on its reinforcement of other goals.

It is testament to the achievements of technology innovators over the past 25 years that technologies such as solar photovoltaics (PV), batteries, light-emitting diodes (LED), advanced nuclear, virtual power plants, next-generation geothermal and several other recent market entrants are mature and competitive enough to be boosted, not sidelined, by these shifts in policy priorities. Despite already having a market foothold, substantial scope remains in all these technology areas to improve performance and reduce costs through R&D and the type of rapid learning that comes only from widespread manufacturing and deployment.

The ways in which these policy priorities influence the outlook for energy technologies varies by country. Some parts of the world have ready access to domestic fossil fuels at low cost, and a focus on energy security or meeting new data centre energy demand may create incentives for innovation in fuel extraction and use. However, most countries do not have such resources, and are looking instead to renewable or nuclear energy to minimise fossil fuel imports.

In June 2025, the European Union adopted a proposal to phase out Russian natural gas imports, and instead focus on enhancing energy efficiency and accelerating the deployment of renewable energy sources. In the People's Republic of China (hereafter "China"), which imports around three-quarters of the oil it uses, almost half of the cars being sold are now electric. Ethiopia has banned imports of internal combustion engine cars and moved to duty-free imports of electric and hybrid vehicles with the aim of reducing its oil import bill and air pollution. In Pakistan, a country that has seen sharp rises in gas import costs in recent years, exemptions to import duties and sales taxes have led to a sharp increase in rooftop PV adoption, with the country's total PV capacity estimated to have passed the total capacity of its conventional generators in 2025. German legislation requires that data centres in the country will need to be supplied by 100% renewable energy from 2027, which also helps the market for co-located battery storage. In the United States, strong government support for data centre expansion underpins several deals between developers and nuclear small modular reactor developers. It also creates potentially large new markets for cutting-edge cooling and waste heat recovery technologies. With defence policy a growing preoccupation for many governments, and the reliance of modern warfare on energy storage, including for drones, national defence procurement legislation is being used more frequently for energy technologies and for supplying their critical minerals. However, it is also the case that innovators depend on policy stability to raise funds and get to market quickly, and experience periods of policy change and uncertainty as a setback.

The State of Energy Innovation 2026 provides examples of how these macro-level developments are influencing energy technology research, development and early adoption. The report's chapters explore how finance is responding to changing perceptions of market attractiveness and the opportunities presented by AI, which technology areas feature in new government innovation policies, and which technologies are well-placed at the intersection of overlapping policy priorities. On the other hand, some technologies are in need of more concerted support to reach their next milestones towards technology readiness and cost-competitiveness. This is especially true for some major, innovative approaches with high potential for long-term emissions reductions, but which risk getting stuck in the so-called valley of death for first-of-a-kind commercial projects. These projects need to shepherd their technologies through the development of scalable business models, offtake contract terms, permitting, customer confidence and social support – sometimes as global trailblazers. Progress in this area is tracked across the IEA's 18 Races to First.

The purpose of this report

Following the first edition in early 2025, this report provides a global stocktake of progress and challenges in energy technology, one that can inform decision makers from the public and private sectors. Innovation is inherently difficult to measure, and its impacts can sometimes appear sudden, even to experts that follow it closely. With a larger share of energy technologies today being modular, mass-manufactured and adopted directly by end-users, sudden exponential growth and disruption of the status quo has become a larger feature of a previously slow-moving and highly centralised sector. The report therefore brings together a range of metrics and horizon-scanning inputs 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 including a survey of over 270 respondents from the research, industry, investment, start-up and policy communities. As networks of experts working on energy technologies, the IEA Technology Collaboration Programmes (TCPs) and Mission Innovation (MI) Missions are without parallel, and their members have contributed many of the insights that illustrate the chapters.

Chapter 1 is dedicated to the highlights of the past year. It 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. The intention is to address the fact that, 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. People who focus on a single sector or are non-experts are often left wondering about the global state of progress based on the selection of headlines and announcements that they see. The chapter also presents updates to the IEA Races to First for large-scale demonstration, and recent award winners honoured by the IEA TCPs and MI Missions, which show where international research communities see significant achievements and promise.

Chapters 2 and 3 provide an overview of key metrics related to finance and tracking of energy innovation progress, including R&D spending, venture capital and patents. In Chapter 4, we turn the focus to the latest notable policy updates from around the world and some of the key policy challenges identified by stakeholders. It concludes with a review of progress against ten policy priorities proposed in The State of Energy Innovation 2025.

The final chapters of the report each focus on one of three specific areas with timely relevance to international deliberations in 2026, in particular the third IEA Energy Innovation Forum. Their inclusion is not a reflection of their relative importance or need for policy support compared with other energy technologies. Rather, it is because they are areas about which there is significant uncertainty among decision makers, and yet key strategic decisions need to be made in the near-term. The three areas are: the link between energy technology innovation and economic competitiveness; technologies to improve electricity grid resilience; and fusion energy. Each of these chapters contains a summary of key knowledge gaps and priority actions to address the barriers to innovation progress.

Technology innovation has the potential to deliver on multiple policy objectives, strengthening energy security and progress towards emissions reductions goals at the same time as driving down costs, thereby making technologies more affordable and forging more competitive businesses for their innovators. It remains a key driver of economic growth. However, the path from idea to implementation is by no means simple: the policy and funding decisions made today will shape the energy sector long into the future. With that in mind, this report aims to provide a strong basis for evidence-informed policy-making and prioritisation.

Results of the expert survey

Input for this report was gathered through consultation, notably a survey that ran between October 2025 and January 2026. This received over 270 responses from representatives across more than 40 countries and 12 domains of energy technology. Questions covered technology highlights, insights on progress in 2025, expectations for 2026, policy practices and strategic priorities (see the Annex). The results have informed the analysis throughout this report. Respondents came from different spheres including policy-making, academic research, corporate R&D, business development and investment. Notably, around one-third of the responses were contributed by experts affiliated with the IEA TCPs.

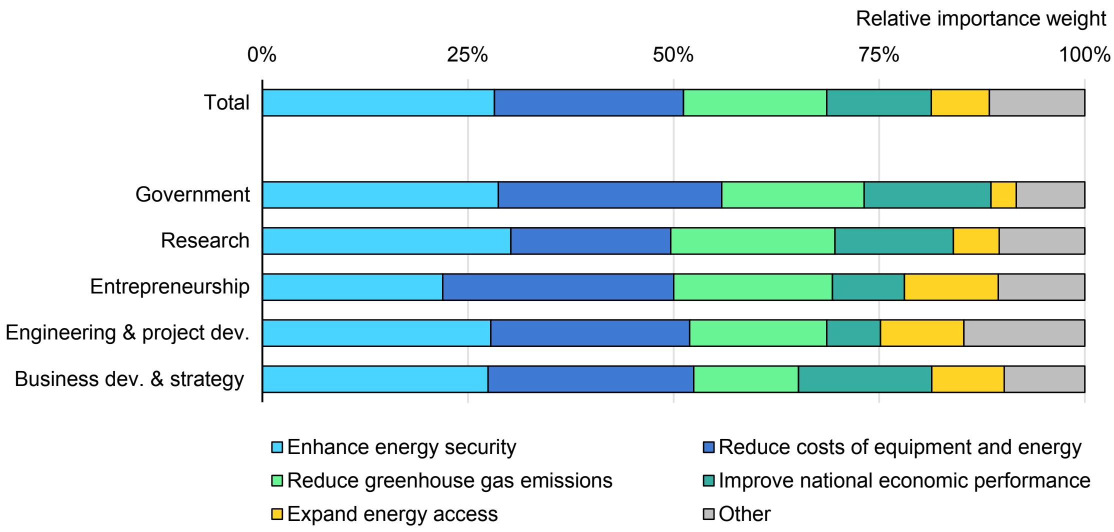
Perceptions of the drivers of energy innovation efforts

As a sign of how energy policy goals are shaping the energy debate, 80% of respondents placed energy security among their top three drivers. When weighting respondents' top three selected drivers, energy security has the largest weight among all options, at almost 30%.[2] Respondents were asked to think beyond the profit motive as a driver, and only entrepreneurs placed cost reductions above energy security as a driver of innovation efforts in 2025. Reducing equipment and energy costs was second, at 23%. Just over half of respondents put "reducing greenhouse gas emissions" among their top three drivers, placing it third, with a weighted share of 17%. Rankings of this driver were highest among respondents working on carbon capture, utilisation and storage (CCUS) and hydrogen.

Overall, the survey results show that practitioners in the innovation community are more sensitive to high-level policy drivers than local or social impacts. Expanding energy access appeared among the top three drivers for one-quarter of respondents, while less than 15% of respondents placed "improving pollution and health outcomes", "enhancing consumer lives", "creating new or better jobs" and "bolstering equality and social welfare". All these drivers had weighted shares lower than 5%.

[2] Relative importance weight is calculated by assigning the following multipliers to the top three ranked drivers of each respondent and summing them: first pick = 3; second pick = 2; third pick = 1. The sum for each driver is divided by the sum of the values of all the drivers.

Survey respondents' perceptions of the more important drivers of energy innovation efforts in 2025, by sector in which they work



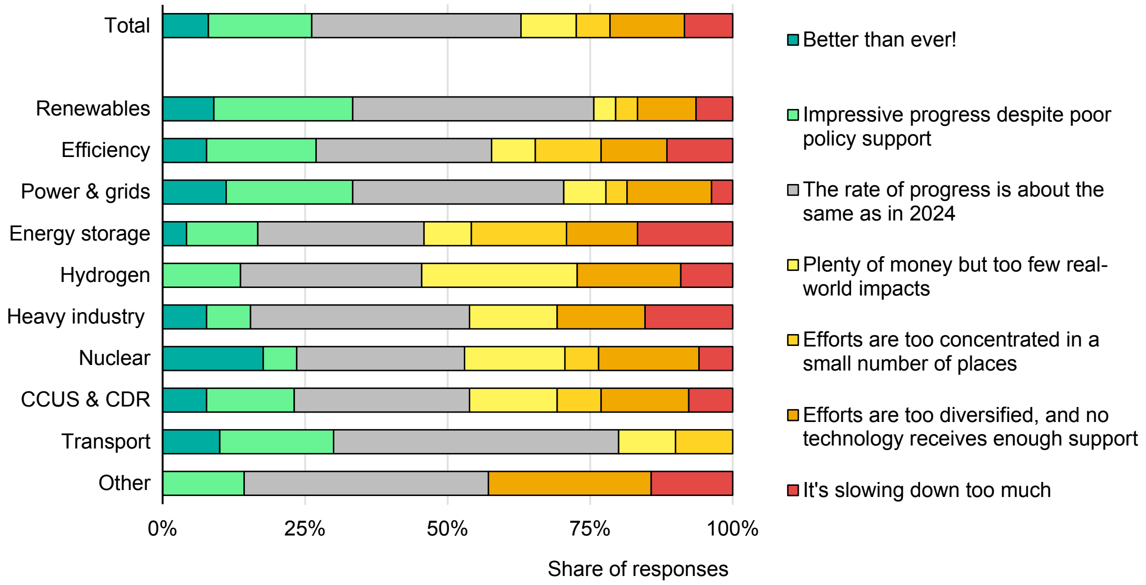
Notes: dev. = development. "Other" includes "improve pollution and health outcomes", "improve the lives of consumers", "support equality of opportunities and social welfare" and "create new or better jobs". Relative importance weighting is calculated by assigning the following multipliers to the top three ranked drivers of each respondent and summing them: first pick = 3; second pick = 2; third pick = 1. The sum for each driver is divided by the sum of the values of all the drivers.

This was the first time that the survey asked this question, and future annual surveys will help to track how experts respond to changing media and political narratives about geopolitical tensions, supply disruptions and climate change. If perceptions translate into motivations, the technologies funded and selected by researchers may shift.

Perceptions of the rate of progress

The survey responses reveal a more tempered outlook on progress in 2025 compared to the previous year, with nearly 40% of respondents indicating that the rate of advancement has remained about the same as in 2024. This is not entirely surprising, given the relatively long cycles typical of energy technology innovation. However, the sentiment of stable progress was not universal across technology areas. For hydrogen, there was a stronger perception that sufficient funding exists, but real-world impacts remain limited, compared with the other technology areas. Among experts in other technology areas, a blend of cautious optimism and growing concerns is apparent, though the overall tone was less positive than in 2024. Nonetheless, one-quarter reported that conditions are "better than ever" or highlighted impressive progress "despite poor policy support" – a decline from 30% the year before. Respondents flagging that innovation is "slowing down too much" rose to 8%, double the previous figure.

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



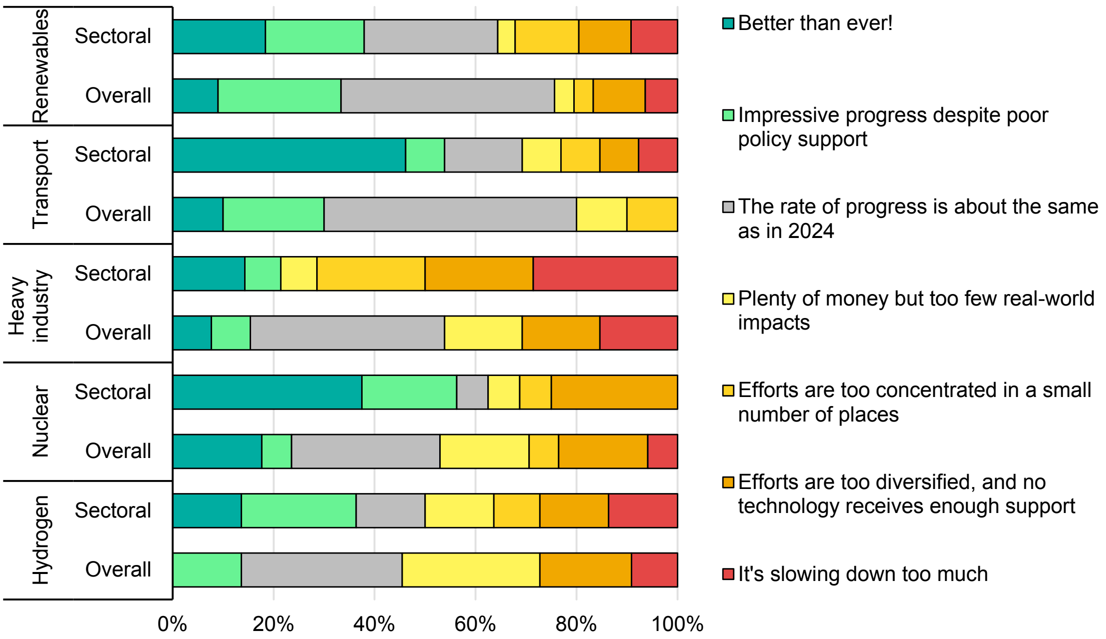
Notes: CCUS = carbon capture, utilisation and storage; CDR = carbon dioxide removal. "Other" includes responses from experts working on critical minerals and energy access, or that did not specify the technology domain in which they work.

Several factors were most frequently cited by respondents as contributing to changes in perception, including political instability, shifting government priorities and economic slowdowns. However, these headwinds did not affect all regions or technologies uniformly. China continued to be viewed as a stronghold for energy innovation, while assessments of Europe and the United States were mixed. The limited number of respondents from emerging markets and developing economies gave a less optimistic perception of energy innovation momentum than the average. Some participants noted that the full effects of recent political changes may not yet be felt, expressing apprehension about potential future disruptions.

Among technology areas, more optimistic perceptions were evident among respondents working on batteries, power grids, nuclear power, geothermal energy and AI, as well as some hydrogen applications such as steelmaking. Respondents viewed solar PV and wind energy as being at a stage of market maturity that makes them less vulnerable to innovation uncertainty, though hampered by regulation that has not kept pace with technological innovation in some cases. This reflects a distinction between more mature and pre-commercial technology areas, for which the dependence on further innovation can influence perceptions of the pace of progress.

Respondents were asked to assess recent progress in their own technology areas, as well as for energy technologies as a whole. This elicited some notable differing perceptions among experts. Among respondents working on hydrogen, the view was, in general, more positive about their own sector than of momentum of energy innovation overall. They consider that there is impressive progress in the hydrogen sector, in line with the IEA's recent assessment. However, around 15% thought that innovation in hydrogen is slowing down too much, reflecting a gloomier outlook that has taken hold among stakeholders in the sector due to recent news about project delays and cancellations. Responses were also muted among respondents from heavy industry, who were relatively disappointed with overall energy innovation progress in 2025, but more concerned with that of their own sector. This raises concerns for a sector characterised by lengthy investment cycles, where delays risk entrenching outdated technologies for decades and impeding the deployment of innovative processes.

Survey respondents' perceptions of progress in overall energy technology innovation and in their domain in the past year



Note: Only selected domains shown, not all survey responses.

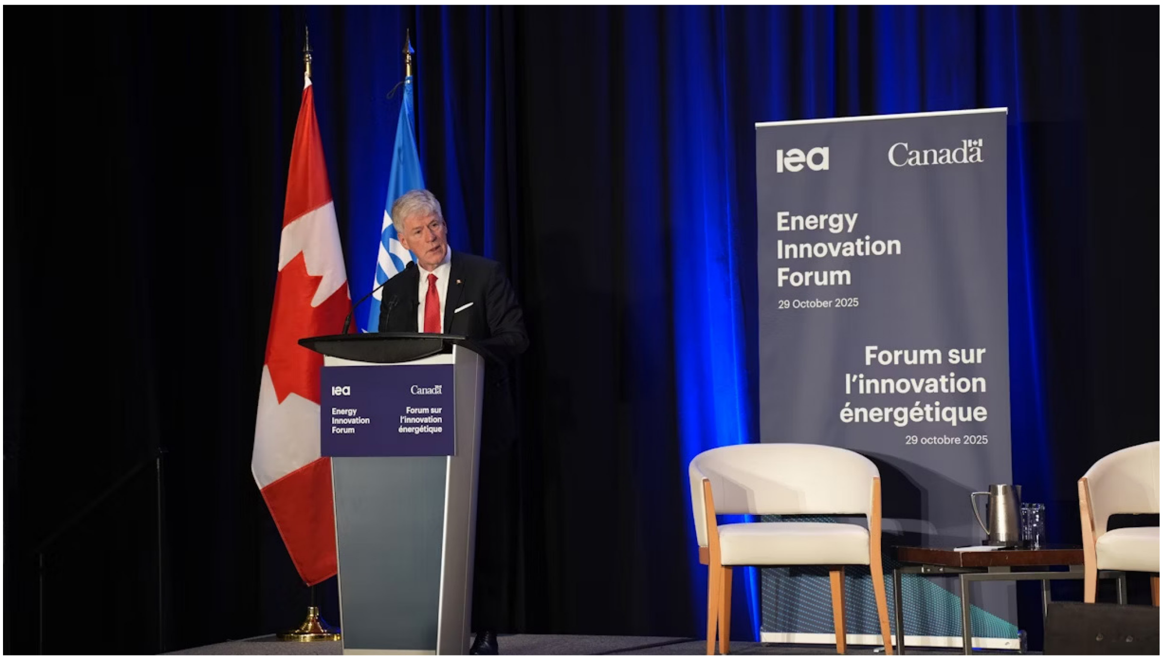
Respondents working on nuclear energy and transport were more upbeat. Just 6% of nuclear experts perceived overall energy innovation as slowing, and none saw this in nuclear itself. In fact, nearly 60% viewed conditions in their sector as better than ever or showing impressive gains despite policy gaps. Over half of respondents from transport technology areas saw overall energy innovation as stable year-on-year, with just 10% deeming it superior, but when evaluating their sector alone, nearly half reported conditions as being better than ever – almost double the equivalent for any other technology area except nuclear. This may reflect a perception of durable momentum for electric vehicles despite policy uncertainty in some countries.

Themes from the IEA Energy Innovation Forum 2025

The IEA convened more than 250 attendees from around the world for its second Energy Innovation Forum, held in Toronto in October 2025, in partnership with the Government of Canada. It brought together policy makers, innovators, investors, researchers and other energy sector stakeholders from around 30 countries to examine the opportunities and risks currently facing energy technology innovation – with the aim of informing decision makers about actions they can take to support innovation in the near term. Innovators from around 40 different start-ups participated in the Forum, along with more than 50 policy makers from multiple governments. The Honourable Tim Hodgson, Canada's Minister of Energy and Natural Resources, gave the welcome address, affirming Canada's commitment to innovation as a means of enabling a reliable, affordable, low-emissions energy system and the export of know-how, technology and resources. He outlined the link with the G7 Energy and Environment Ministers' Meeting the following day, to which the Forum's conclusions were relayed.

Interventions throughout the plenary sessions reflected the multiple drivers for energy innovation today. In his keynote speech, John Stackhouse, Vice President at the Royal Bank of Canada, underscored the notion that a new wave of capital could be unleashed to deliver technologies that shore up energy and data security around the world. He outlined an emerging view that access to energy, data and critical minerals will determine national prosperity this century, creating a huge opportunity for technologies at the intersection of these imperatives. However, he also warned that AI and geopolitical events are compressing timelines: long term is now just six months ahead.

Speakers in the opening exchanges reiterated that "policy really matters" for energy technology innovation, whether it is related to programmes to fund R&D for promising new ideas, establishing standards or sending robust market signals to the private sector. Yet policy and regulation can also lag behind and be unprepared for technologies becoming ready for market entry. A range of technologies were emphasised as being primed for an inflow of investment wherever business models and market signals are attractive, including lithium extraction from unconventional brines; small modular nuclear reactors; sustainable aviation fuel; smart transformers; direct air capture of CO_2; and low-carbon shipping technologies.



The Honourable Tim Hodgson, Canada's Minister of Energy and Natural Resources, addresses the second IEA Energy Innovation Forum

Four project developers presented their progress towards the IEA Races to First milestones – for hydrogen-based liquid aviation fuel, enhanced geothermal, low-emissions aluminium production and direct air capture and storage of CO_2. Besides the technical leadership that these innovative companies are demonstrating, the presentations emphasised two key commonalities. Firstly, first-of-a-kind commercial projects that can complete the IEA's Races must solve a much wider set of challenges than the purely technical, including building public and political support, securing industrial partners and customers, stress-testing new permitting regimes, designing replicable engineering packages, and proving an untested business model. Secondly, the four projects had to overcome a financing challenge that continues to stymie scale-up. Sometimes called the "missing middle", the finance that large projects of this kind require is too much for venture capitalists to fund and too small and risky for traditional sources of capital, such as banks. The projects have found different ways to reach financial close, such as philanthropic grants, joint ventures with major industrial customers and long-term offtake contracts. In addition, all have benefited from government support to get to the construction phase, whether grants, production tax credits or export credits – some of which has come from third countries. A range of public-private partnership models will be critical to success in the 18 IEA Races to First.

In the other plenary sessions, public and private sector speakers responded to the messages of the State of Energy Innovation 2025 report. The European Commission stressed the importance of international collaboration, especially on AI and digitalisation, and reducing barriers to accessing EU innovation funds. It confirmed that the European Union seeks to attract international innovators, including with its recent Startup and Scaleup Strategy. Other speakers highlighted the roles of governments in faster permitting, ensuring that the market rewards innovation success, encouraging the accrual of trade secrets, standardisation and facilitating cross-sectoral co-operation. Speakers pointed out that policy can change – for better or worse – on a timescale that is far faster than the many years it takes for energy hardware to steadily scale up from lab to market.

Speakers from Canada's indigenous communities, Kenya, Singapore and Ukraine gave striking examples of the global nature of the innovation ecosystem. They demonstrated that researchers and investors will devise original, affordable and effective solutions for their local contexts when they have the resources to do so, and that these can become international benchmarks. In these places, technological innovation holds the promise of driving economic growth and building sustainable infrastructure from the ground up.

AI for innovation, battery mineral diversity, and carbon dioxide removal

The first breakout session asked whether AI can dramatically change the pace of clean energy technology innovation. Speakers cited impressive examples of how AI scientists are already reshaping how research is done, including for robots that design and run chemical experiments and algorithms that search vast datasets to identify cutting-edge new materials. The discussion alighted on several key energy areas where AI is widely expected to transform innovation: batteries, fuel cells, lasers and corrosion-resistant materials. However, the promise of supercharging innovation with AI is highly contingent on the availability of dependable large, quality datasets of appropriate molecules and materials, as well as methods for rapidly predicting and testing performance in real-world applications. Recommended actions include providing a forum for discussion across domains, facilitated by the IEA or Mission Innovation; international co-operation to identify and prioritise the energy problems that AI can help solve; targeted funding for labs that help to democratise access to costly tools; support for generalisable models; and communication of the potential of these AI applications to the R&D community.

Breakout sessions at the second IEA Energy Innovation Forum, 29 October 2025

The second breakout session took up the topic of how innovation can contribute to more diverse battery mineral supplies. The technology landscape is broad, covering new methods for obtaining critical minerals from domestic and diverse locations, including recycling of batteries, and advanced battery chemistries that reduce demand for critical minerals. In recent years, there has been a surge in innovative activity in response to supply chain concerns, and R&D has significantly strengthened the outlook for competitive production in the G7 and partner countries. However, the investment proposition frequently relies on co-ordination between demand and supply – including environmental criteria, local benefits of investment, downstream offtake and electric vehicle demand – that governments are best-placed to address. Long-term competitiveness depends on clear demand signals, and public-private support to help innovators test their solutions commercially. Recommended actions proposed included co-operation between trading partners; facilitation of partnerships and alliances between innovators and customers; helping an international portfolio of innovators to generate results at scale to secure customers; ensuring that permitting processes are not an unnecessary barrier to scaling up new technologies; considering "full stack" support that starts from the demand for the batteries and shares private sector risks with tools such as equity, R&D grants, price floors, workforce training, or regulation of waste minerals.

A third breakout session considered how to bring down the price of carbon dioxide removal more quickly. This technology area has witnessed tremendous progress in recent years, achieving scales that put its technical effectiveness beyond doubt. Government funding has been central to this effort and now private capital is stepping in to pay upfront for future removals. However, the path to becoming a well-developed new industrial sector is steep and innovators must be supported with access to customers, common standards and opportunities to test at scale. Canada's leadership was appreciated by participants: at the Forum, NorthX Climate Tech, supported by the Canadian government, announced new investments into carbon removal ventures, Arca Climate technologies announced an offtake agreement with Microsoft, and the Government of Canada announced a new prize initiative. Recommended actions included: prioritise international standards to create an international market; strong, reliable and transparent markets, including through public procurement; value the co-benefits of novel technologies, such as waste remediation and jobs for existing skilled workers; focus on how more international knowledge exchange can contribute to faster cost reduction; and support potential customers to learn about the technology status and its potential.

Chapter 1. Recent developments

The year 2025 saw a number of significant developments in energy innovation, from advances in fusion energy research that are capturing the imagination of investors, to the market launch of new products that can help secure the grids underpinning the age of electricity.

For this second edition of The State of Energy Innovation, we have again compiled noteworthy examples of technological progress from the past year. The technologies listed below have been selected to reflect the broad scope of innovation progress taking place in different sectors and across the world; the list is not intended to be exhaustive. It is intended to draw the attention of decision makers to key milestones in energy innovation and provide insights into the developments on the horizon for the coming years.

The analysis draws on the latest update to the ETP Energy Technology Guide, as well as a recent survey of technology and innovation experts, including from governments and the private sector (see the Introduction to this report).

The innovations listed in this chapter are divided into five categories:

- **Prominent advances in research and prototyping**: reported results from projects up to technology readiness level (TRL) 6 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, service or licensed industrial process based on a technology that has reached a first-of-a-kind commercial demonstration (TRL 8) or full commercial operation in the relevant environment (TRL 9).
- **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 lists on the following pages provide a snapshot of promising energy innovations from around the world in 2025: 155 highlights are available to explore online.

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 on 640 technologies 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 as information becomes available.

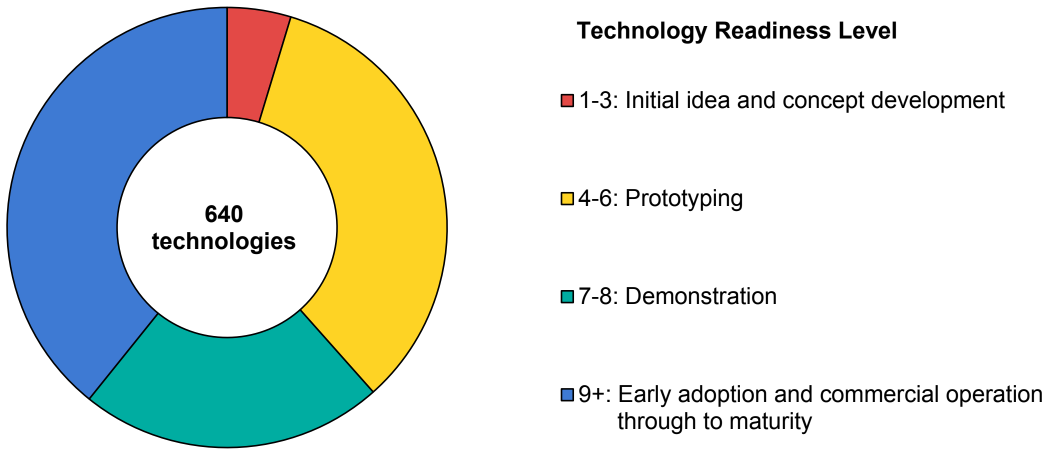
Information on the global level of technology maturity is standardised across technologies using the TRL scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and used in many government agencies since the 1990s, the TRL provides a snapshot 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 lithium-ion (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. Another reason for continued innovation relates to refinement to make a technology fit for the geography, climate, regulations and sources of energy in a new market. Beyond the TRL 9 stage, when technological risk has largely been eliminated, the IEA scale assigns one of three indicators of adoption status – awaiting adoption, building momentum, or commercial in many markets. The intention is to provide a simple signal to policy makers of where further support may be needed to overcome non-technical barriers, or where technically proven products remain uncompetitive.

Notable upgrades in technology readiness

The ETP Energy Technology Guide is the IEA framework to identify and track key energy technologies that can address policy priorities. The guide helps users to follow progress in the development of products and services with the potential to reduce emissions and increase the security and affordability of the energy system.

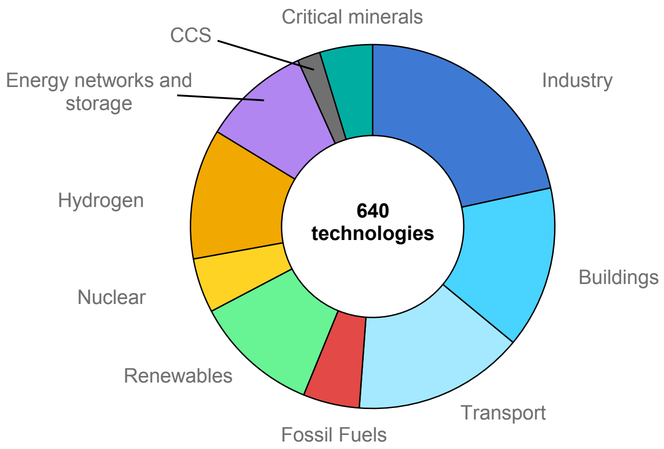
Energy Technology Guide entries classified by technology readiness level as of the end of 2025



Source: IEA ETP Energy Technology Guide.

The latest iteration of the Energy Technology Guide contains 640 individual technologies. These technologies have primarily been identified in the course of IEA analysis, especially its modelling of future energy systems, and also through review of stakeholder submissions. Since the guide was first published in 2020, the number of technologies has grown, and existing entries have been updated. As well as low-TRL technologies being added as more details about them become available, some of the expansion relates to the division of higher-TRL technology areas into more specific branches of ongoing innovation. This year, technologies related to fusion energy, nuclear fission, geothermal (included in the renewables category), and critical mineral technologies accounted for most of the additions, in part as a reflection of recent IEA work on the topics. On average, 50 technologies have their TRL updated upwards every year, or roughly 10% of all the technologies we track. This metric indicates continuing dynamism across a range of high-potential technologies for the energy system.

Energy Technology Guide entries classified by sector, 2025

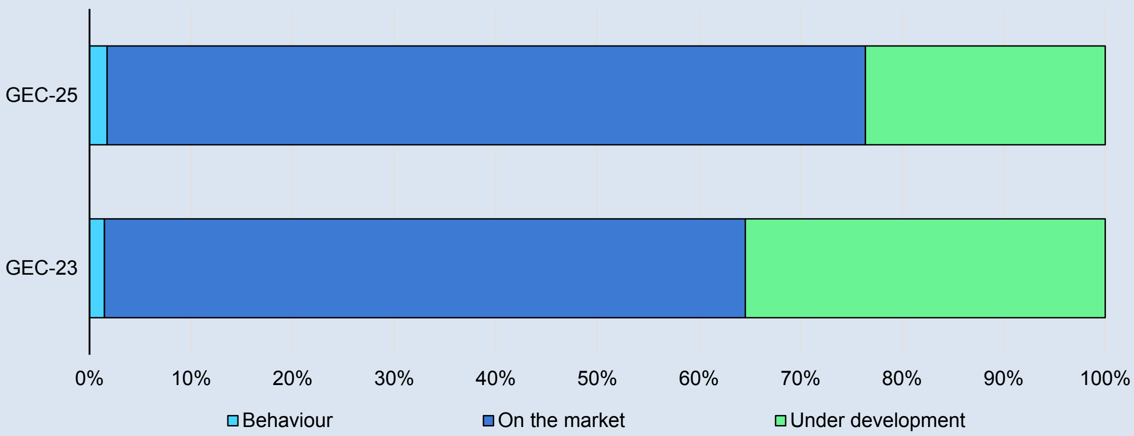


Note: CCS = Carbon capture and storage.
Source: IEA ETP Energy Technology Guide.

Technology innovation requirements for net zero emissions by 2050

Since 2020, the IEA has estimated how emissions reductions in 2050 in successive versions of its Net Zero Emissions by 2050 Scenario (NZE Scenario) map onto technology maturities. In 2023, we reported that around 35% of the reductions would require technologies not yet commercially available. In the 2025 update of the scenario, the share has fallen to around one-quarter.

CO_2 emissions reductions in 2050 relative to the base year by technology maturity in the 2023 and 2025 Net Zero Emissions by 2050 Scenarios



Note: GEC = Global Energy and Climate Model.

For energy policy makers, this result is reassuring. Not only is the technical feasibility of a low-emissions energy system higher, it also shows that the innovation process can be relied upon to make technologies available. With good judgement, there is no reason to discount a long-term scenario just because it anticipates further technological progress. In the case of the 2025 update, progress with battery chemistry and design means that we now consider nearly all battery technologies needed for various applications in the NZE Scenario to be sufficiently developed. This includes technologies with low critical mineral intensity (i.e. sodium-ion) as well as batteries needed for most (but not all) heavy freight applications. In addition, there has also been progress in the field of synthetic fuels use, including in ammonia- and methanol-powered ships.

However, another – albeit smaller – part of the change in the share of pre-commercial technologies is due to adjustments in the technological composition in the scenario. Changes in relative expected costs, projects' development and policy preferences result in different assumption about technology diffusion. Technologies related to electrification and their use for net zero emissions continue to advance gradually as a share of final consumption, and renewable electricity capacity expands by about one-fifth in the latest scenario compared to the previous one. This is aided by battery storage systems, which see an even higher increase in the deployment to 2050 in terms of power and energy capacity. Conversely, there is less reliance on certain large-scale applications for which first-of-a-kind projects are currently under construction, such as for carbon capture, utilisation and storage (CCUS) for process emissions, which is down by one-fifth, and hydrogen, for which overall demand has been scaled down by one-third in 2050 compared to the previous NZE Scenario vintage, reflecting the rate of progress in the sector.

With around one-quarter of emissions reductions still dependent on technologies that have yet to be proven at scale, this result does not reduce the importance of technology innovation for meeting countries' climate goals. The remaining emissions are in sectors without attractive alternatives to the ones under development. In addition, the scenario inherently includes innovation in the form of continual cost declines and performance improvement for many technologies, and these will be delivered by healthy innovation ecosystems, not just economies of scale. In addition, any additional improvements in the competitiveness of low-emissions technologies will speed up their deployment or reduce the need for continued policy support.

Prominent advances in research and prototyping

This section presents selected highlights from 2025 in the area of scientific research and early-stage testing (up to TRL 6). The five examples represent significant progress in a range of technology areas that, if scaled up and cost-competitive, could help address key energy system challenges.

TRL
3
Nuclear fusion
Advances in sustained plasma operation in stellarators at high performance demonstrate clear progress toward magnetic confinement fusion

TRL
9
Solar PV
Recent progress in crystalline silicon and silicon-perovskite tandem technologies raising achievable solar-cell efficiencies

TRL
4 → 5
Buildings
First kilowatt-scale elastocaloric cooling system demonstrated at commercial level

TRL
4 → 5
Road transport / Batteries
Lithium-ion batteries with high performance and lower critical mineral content

TRL
7
Critical minerals
High-efficiency spheroidisation achieved for biomass-derived battery-grade graphite

1. Advances in sustained plasma operation in stellarators at high performance demonstrate clear progress toward magnetic confinement fusion

Stellarators represent an alternative type of magnetic confinement fusion energy from tokamaks. Unlike tokamaks, whose plasma records in China and France were reported in The State of Energy Innovation 2025, stellarators do not require an additional electrical current to be created within the plasma. In 2025, Wendelstein 7-X, a research facility built and operated by the Max Planck Institute for Plasma Physics in Germany, set a world record by maintaining a plasma at elevated temperature and density and for 43 seconds, reaching the highest so-called "triple product" ever reached for long plasma durations in stellarators. This is the first time a stellarator has matched – with a different fuel – the long-pulse performance levels previously associated with large tokamaks. Wendelstein 7-X has received total public funding of around USD 1.7 billion over the period 1995-2021, mostly from the German government, the European Union and the United States. Although these results are encouraging, fusion energy, regardless of the approach, still has a long way to go before commercialisation (Chapter 7).

2. Recent progress in crystalline silicon and silicon-perovskite tandem technologies raises achievable solar-cell efficiencies

Progress in high-efficiency perovskite tandem solar cells holds the promise for further solar PV cost declines as existing silicon-based technologies reach their performance limits. In January 2025, LONGi, a Chinese PV manufacturer, announced a crystalline silicon-perovskite tandem solar cell with a certified power conversion efficiency of 33%, on a 260.9 cm^2 aperture area. This marks a nearly 20% increase compared to single-junction crystalline silicon solar cells and represents the world's first 33% efficiency milestone at mass-producible dimensions. In parallel, a monolithic back-contact crystalline silicon module from LONGi achieved an efficiency of >26%, thereby extending the upper performance boundary for single-junction silicon modules produced at commercial scale.

3. First kilowatt-scale elastocaloric cooling system demonstrated at commercial level

Progress in elastocaloric solid-state cooling systems points to a new class of high-efficiency, low-carbon thermal technologies capable of significantly increasing energy efficiency for cooling in buildings and industrial processes. In February 2025, Hong Kong University of Science and Technology tested a solid-state cooling system that achieves about 1.3 kW[3] of cooling output, a key advance on previous elastocaloric prototypes that were mostly below 300 W. The system uses shape-memory alloys, a class of materials that release or absorb heat when compressed or stretched. It then transfers heat through a high-conductivity nanofluid. In a demonstration, the cooling system lowered the temperature in a small (2.7 m^3) test room by roughly 10°C. Elastocaloric cooling systems are one possible pathway for solid-state cooling technologies, which promise higher efficiency compared to baseline vapour compression cycles and avoid the use of cooling fluids that can damage the environment.

4. Lithium-ion batteries with high performance and lower critical mineral content

Researchers in the United States are advancing the R&D of lithium-ion (Li-ion) batteries with manganese-rich cathodes. Manganese-rich cathodes for Li-ion can

[3] Zhou et al. (2025), Achieving kilowatt-scale elastocaloric cooling by a multi-cell architecture, Nature, https://doi.org/10.1038/s41586-024-08549-9.

potentially substitute significant amounts of expensive critical minerals such as nickel and cobalt with low-cost manganese without significant performance penalties compared to traditional lithium nickel manganese cobalt oxide (NMC) chemistries. In May 2025, GM, a US carmaker, and LG Energy, a Korean battery producer, claimed that their prismatic cells using this technology overcame stability issues and achieved an energy density that is 33% higher than the market-leading chemistries today. Ford, a US carmaker, is also advancing this technology, and claims to have achieved pilot-scale production.

5. High-efficiency spheroidisation achieved for biomass-derived battery-grade graphite

High-yield graphite spheroidisation using renewable biomass offers a pathway to lower-cost, lower-energy and lower-carbon battery-grade graphite. In early 2025, CarbonScape, a New Zealand start-up, reported that its biomass-derived process achieved a 90% spheroidisation yield on a pilot plant, far higher the 30-60% typical of conventional natural graphite spheroidisation and above the 80% seen at best in synthetic-graphite producers. The process targets the material-loss bottleneck in conventional spheroidisation to improve the production efficiency. The aim is to produce high energy density anode material while offering an alternative source of supply. CarbonScape's development has been supported by the New Zealand government.

First-of-a-kind pilot and demo achievements

This section presents selected highlights from 2025 in the area of technology demonstration in real-world conditions, whether large pilot or first-of-a-kind commercial installation (TRL 6 to TRL 9). The seven examples demonstrate performance for the first time at scales relevant for future commercial deployment or in a specific regional context, thereby contributing evidence about commercial potential across a range of relevant technology areas.

TRL
8 → 9
Thermal storage
The largest industrial solid-state thermal battery commences commercial operation

TRL
5 → 6
Hydrogen
Geological hydrogen storage demonstration completes successful testing

TRL
9
CCUS
First commercial CO2 terminal and storage hub begins operations

TRL
5 → 6
Bioenergy
Completion of world's largest hydrothermal liquefaction facility

TRL
8
Geothermal
Operational EGS in super-hot geothermal conditions and advanced drilling technologies demonstrated

TRL
4 → 6
Industry / Iron and Steel
H2-direct reduced iron production begins in Namibia

TRL
7 → 8
Industry / Aluminium
New electric boilers for steam production at alumina refinery plant are helping to prove the technology

TRL
7
Shipping
Kite propulsion for ships completes new round of land-based tests

6. The largest industrial solid-state thermal battery commences commercial operation

Industrial heat batteries allow renewable electricity to be converted into high-temperature process heat, offering a pathway to lower-carbon industrial production. In October 2025, Rondo Energy, a US start-up, started commercial operation of a 100 MWh industrial heat storage device. Electricity – in this case from solar PV – is used to warm bricks to above 1 000°C and the heat is discharged as steam to a factory in the United States. Announced efficiency is around 97%, with less than 1% heat loss per day. In November 2025, a smaller 33 MWh heat battery was commissioned by Rondo Energy in Thailand, where the heat is used to generate electricity for a cement plant. With projects running on four continents, heat batteries can now be considered a mature technology which can help industrial processes to use electricity as a heat source, and store variable renewable power.

7. Geological hydrogen storage demonstration completes successful testing

Large-scale underground hydrogen storage provides a missing link between variable hydrogen production from renewable energy and continuous hydrogen use in power generation and industry. In May 2025, HyPSTER, a European research consortium, announced the completion of 4 months of hydrogen storage testing in salt caverns in France, involving approximately 100 injection-withdrawal cycles under varying conditions of pressure and cycling speed, successfully validating its feasibility. As hydrogen supply expands, underground geological facilities could be needed for storage to balance supply fluctuations caused by variable renewable electricity used in electrolysers and from seasonal changes in demand, as well as to bolster energy security. With a total budget of roughly USD 17 million, around one-third of HyPSTER's costs are covered by grants from EU member states, with the remaining financed by consortium partners through co-financing and in-kind contributions.

8. First commercial CO_2 terminal and storage hub begins operations

Large-scale carbon capture and storage enables CO_2 from industrial plants to be permanently stored underground, providing a pathway to reduce emissions from sectors where other alternatives are technically unavailable. In August 2025, Northern Lights, a CO_2 storage project consortium, received the first shipped CO_2 volumes from Heidelberg Materials' Brevik cement plant at its CO_2 receiving terminal in Øygarden. The terminal offloads and temporarily stores liquefied CO_2 before it is pumped through a 100 km subsea pipeline to offshore injection wells 2 600 metres below the seabed. After commencing CO_2 capture in June 2025, around half of the cement plant's emissions will be captured, resulting in roughly 400 000 tonnes of CO_2 stored annually. The CO_2 is captured from clinker production via amine-based CCS technology. These events mark a milestone for both CO_2 storage technology, and capture technology at cement facilities. Northern Lights has been enabled by the equivalent of USD 2.2 billion from the Norwegian government to cover nearly two-thirds of the costs of its first 10 years of operation, as well as about USD 140 million from the European Union.

9. Completion of world's largest hydrothermal liquefaction facility

Biomass-to-bio-oil processes convert waste biomass into low-carbon fuels and industrial feedstocks, providing an alternative to fossil fuels for transport, industry and materials production. In 2025, Arbios Biotech, a subsidiary of Australian biotechnology company Licella, completed construction of its Chuntoh Ghuna facility in Canada. Announced in 2021, the plant is designed to process 25 ktpa (dry) of wood residues into 50 000 barrels of bio-oil annually, making it the largest hydrothermal liquefaction plant worldwide. In 2018, of the total USD 16 million project cost, the Government of Canada contributed approximatively 20% with additional public support from British Columbia grants and low-carbon fuel incentives.

10. Operational EGS in super-hot geothermal conditions and advanced drilling technologies demonstrated

Technical advances in drilling technologies are required to enable ultra-high-temperature Enhanced Geothermal Systems (EGS), which unlock a new class of geothermal power plants with more heat extracted per well and therefore higher efficiency and power output. These advances could allow geothermal energy to expand beyond regions with favourable geology, enabling much wider deployment of this energy source. Mazama Energy, a US start-up, announced a successful pilot with a bottomhole temperature of 331°C – and therefore considered super-hot – in tight volcanic rock while maintaining fluid and heat circulation. This is the highest reported EGS temperature, and the company plans to reach more than 400°C with a power output of 15 MW in 2026. The drilling rate, which averaged 23 metres per hour through hard rock (granite, basalt and granodiorite) was also an achievement, as was the uninterrupted operation for around 0.8 km without drill-bit or tool failures. These achievements relied on multiple cutting-edge techniques: novel fracturing processes; planned directional drilling; drill-bit design; control of weight-on-bit; rotary speed; cuttings management; tailored drilling fluids; and cooling strategies. Such hot environments were previously considered too risky for geothermal development. Mazama Energy's pilot plant was enabled by USD 20 million from the US government.

11. H_2-direct reduced iron production begins in Namibia

Hydrogen-based iron production establishes a new industrial process for making iron, replacing coal-based blast furnaces. In April 2025, HyIron, a consortium of German companies, completed construction of its pilot plant in Namibia and is now ramping up production. The plant will initially produce 15 000 tonnes/year of direct reduced iron (DRI) by reducing iron ore with hydrogen generated from water and renewable electricity, with the objective to reach 200 000 tonnes/year. It uses hydrogen-based rotary-kiln reduction to process iron ore fines directly, avoiding costly agglomeration steps, and a 12 MW onsite electrolyser. Hydrogen DRI production is one of the most advanced technologies for production of low-emission iron. With a total budget of approximatively USD 32 million, HyIron received over 40% of this amount as a grant from Germany in 2023, and grants from the European Union and The Netherlands in 2025, among others.

12. New electric boilers for steam production at an alumina refinery are helping to prove the technology

Electric boilers provide an alternative to fossil-fuel-fired boilers used in the refining of bauxite into alumina – a highly energy-intensive process. Three years of operating a 60 MW electric boiler at the Alunorte alumina refinery in Brazil, which is owned by Norwegian Aluminium producer Hydro, have confirmed the reliability of a technology that had not previously been operated under continuous loads or for large-scale steam supply. Two additional electric boilers (each around 50 MW) were subsequently installed and began operation in 2025 at the site, which can now produce 270 tonnes of steam per hour from electricity. Traditional electric boilers cannot meet the high-temperature calcination needs of alumina refining, but could in principle supply all low-temperature heat, which accounts for around two-thirds of total heat demand. A wide range of sectors and sites in different industries use high-pressure steam, potentially providing a large market for this technology. Heat pumps remain a potential competitor for this type of electrical heating, despite the recent termination of a mechanical vapour recompression project with a similar objective.

13. Kite propulsion for ships completes new round of land-based tests

Wind-assisted propulsion for shipping can significantly reduce fuel consumption needs. Some wind propulsion technologies are already in the early stages of market uptake, largely based on tall cylindrical rotor sails installed on deck. Around 10-20 new sales and seaborne tests of on-deck sails for tankers and general cargo vessels went ahead in 2025, supplied by companies from Finland, Spain and the United Kingdom. However, a separate technology – kites – took an innovation step forward in 2025 and has the potential to exploit higher wind speeds and take up less deck space. On-board kite prototypes have already been tested by various companies, but large-scale operations still need testing. In 2025, K Line, a Japanese transportation company, finished onshore testing of its 300 m^2 kite with the aim to develop a 1 000 m^2 kite. The technology was initially developed by Airseas, a French start-up acquired by K Line in 2024. This reflects an uptick of interest in wind propulsion, though one policy driver, the International Maritime Organization's proposed regulations on ships' GHG emissions, was postponed in 2025.

Announced commitments to go to the next level

This section presents selected announcements from 2025 of investment decisions or other firm commitments to take significant risks to scale up an emerging technology. Unlike the previous categories, these highlights are not results of experimental or operational testing, but rather signals of private sector readiness to push towards the next TRL. The six examples are mostly of large pilot or first-ok-a-kind commercial-scale projects and they represent key non-technical milestones across a range of relevant technology areas.

TRL
8
Nuclear / Fission
Announcements to deploy SMRs

TRL
6 → 7
Hydrogen / e-fuels
Synthetic fuel plants are coming online at ever larger scales

TRL
5
Aviation
Additional investments announced to develop a full-scale demonstrator blended wing body aircraft

TRL
8
Wind
Turbine manufacturer announces plans for 50 MW floating wind turbine

TRL
6
Shipping
Commercial-scale ammonia-fuelled ship engines have completed full-load trials

TRL
6
Industry / Cement
Scale-ups announced for electrification of high-temperature heat in cement manufacturing

14. Announcements to deploy water-cooled SMRs

A multi-gigawatt commitment to deploy small modular reactors (SMRs) marks a significant step forward for smaller nuclear reactors. It indicates a willingness to invest in their promised attributes of faster construction speed and easier placement near electricity-hungry consumers. In September 2025, the Tennessee Valley Authority, a US utility company, signed an agreement with ENTRA1 Energy, a new nuclear developer, to buy electricity output from up to 78 standardised 77 MW light water reactors at multiple locations. These SMRs are to be manufactured in series by NuScale Power, a 19-year-old company with no operational reactors to date. While no timeline is available for the project, if successful it will help develop the regulatory process and pave the way for more new entrants. Also in 2025, the US government awarded USD 800 million to Tennessee Valley Authority and Holtec, a technology developer, to support SMR projects, including two Holtec SMR-300 units and a GE Hitachi BWRX-300 unit. As reported in The State of Energy Innovation 2025, the latter design is already under preparation in Canada, for which construction was approved in 2025.

15. Synthetic fuel plants are coming online at ever larger scales

Large-scale plants coming online show hydrogen-based synthetic liquid fuel production reaching commercial volumes. In June 2025, INERATEC, a German start-up, began operating the largest such plant in Europe, a 2.5 ktpa facility in Germany. The inputs to its Fischer-Tropsch reactor are by-product hydrogen from a chlor-alkali plant and biogenic CO_2. The plant also produces saleable waxes. In May 2025, Infinium, a US start-up, started construction of Project Roadrunner in the United States, which will have a capacity of 23 ktpa, nearly ten times larger than INERATEC's plant. While these projects are still orders of magnitude smaller than conventional fuel refineries, the scale-up is moving quickly and providing operational knowledge. The production of these fuels, which can be used without major engine modifications, is a key technology to provide low-emissions options for sectors such as aviation. INERATEC's project was enabled by around USD 45 million of venture debt from the public European Investment Bank.

16. Additional investments announced to develop a full-scale demonstrator blended wing body aircraft

Growing commitments to blended wing body aircraft strengthen the prospects for a step-change in long-haul aviation efficiency. In June 2025, United Airlines, a US airline, invested in JetZero, a US start-up that is developing blended wing body aircraft intended to carry more than 200 passengers. The design could deliver up to a 50% reduction in fuel burn per passenger-mile by significantly lowering aerodynamic drag. As part of the deal, United Airlines agreed to order up to 200 planes and if conditions are met, undertake a successful demonstration flight in 2027. JetZero received USD 235 million from the US Air Force in 2023. To date, prototypes of such aircraft have only had wingspans up to 10 metres (compared to over 50 metres for JetZero's design) and been remote controlled. If JetZero meets its targeted milestones, a step-change in aircraft efficiency improvements may be possible.

17. Turbine manufacturer announces plans for 50 MW floating wind turbine

A new generation of large-scale floating turbines may open up a pathway to cost reduction for a wind energy technology that can be deployed in deep-sea areas. In October 2025, Mingyang Smart Energy, a Chinese wind turbine manufacturer, announced plans to develop the world's largest floating offshore wind turbine. The floating turbine would achieve 50 MW capacity with a twin-head, v-shaped design, potentially redefining the future of deep-water wind power. It builds on the firm's earlier OceanX platform, which was tested at 16.6 MW in 2024. Twin rotors increase the power capacity per floating platform, which could reduce electricity generation costs. The technology is still being demonstrated, but this announcement sets new levels of ambition in terms of economies of scale. Floating wind turbines could significantly expand the number of sites suitable for offshore electricity production.

18. Commercial-scale ammonia-fuelled ship engines have completed full-load trials

Successful full-scale tests of ammonia-fuelled marine engines demonstrate the viability of ammonia as a combustion fuel, with potential for major reductions in CO_2 emissions in long-distance shipping. In August 2025, J-ENG, a Japanese engine maker, completed testing of its 2-stroke dual-fuel ammonia engine. It is expected to equip a medium-sized gas carrier at a shipyard in 2026. In July, engines designed by WinGD, a Swiss company, became the first ammonia dual-fuel two-stroke engines to be tested and successfully installed in new LPG/ammonia carriers being built by EXMAR, a Belgian technology firm, in Korea. These vessels will be similar in size to the medium-sized gas carrier targeted by J-ENG and are set to enter service in 2026. Also, in 2025, Everllence (formerly MAN Energy Solutions), a German engine maker, announced pilot installations of its two-stroke ammonia engine starting in early 2026, including on two large ammonia carriers, a large bulk carrier and vehicle carriers.

19. Scale-ups announced for electrification of high-temperature heat in cement manufacturing

The high-temperature heat used in cement manufacturing remains a significant challenge for electrification, but announcements in 2025 hint at progress. In

November 2025, Indian manufacturer Adani Cement and Finnish technology developer Coolbrook announced that a novel electrification technology, the RotoDynamic Heater, would be deployed to provide electrified high-temperature heat to the pre-calciner at a cement plant in Andhra Pradesh, India. In addition, Heidelberg Materials successfully operated a 300 kW plasma heated cement kiln in Sweden in 2025 through the EU-funded ELECTRA project, and announced plans to run a 1 MW pilot kiln in 2026. The Leilac project in Belgium also installed a calciner tube suitable for electrification and flexible hybrid configurations, announcing successful tests of 21 days of continuous and flexible operation in September 2025.

New products and processes hitting the market

This section presents selected highlights from 2025 in the area of technologies that have reached pre-commercial and commercial readiness (TRL 8-9) and are being brought to the market as commercial products, services or industrial processes. The five examples represent a variety of technology areas that could help address key energy system challenges, and indicate that key technical, regulatory and business hurdles have been overcome.

TRL
7 → 8
Buildings

A new air-conditioning system achieves thermal energy storage by decoupling dehumidification and cooling

TRL
7 → 9
Road transport / Ultra-fast charging

Launch of mass production of the fastest-charging EV platform, reducing recharge times to those approaching gasoline refuelling

TRL
7 → 8
Electricity grids

A new grid-stabilising unit uses supercapacitors to deliver active and reactive power for voltage and frequency support

TRL
9
Oil & Gas

Real-time methane emissions detection equipment to curtail methane footprint is being rolled out worldwide

TRL
8 → 9
Industry / Batteries

Commercial deployment of sodium-ion batteries begins in multiple sectors

20. A new air-conditioning system achieves thermal energy storage by decoupling dehumidification and cooling

Air-conditioning technologies with built-in thermal storage are emerging as a way to sharply reduce peak electricity demand and enhance grid flexibility. Blue Frontier, a US start-up launched in collaboration with a US government laboratory, developed an air-conditioning system that integrates cooling, dehumidification, and energy storage in a single unit. The technology, which is scheduled to enter small-series production in the near term, separates cooling and dehumidification using a liquid desiccant that absorbs moisture before the air is cooled. The desiccant is regenerated later, away from peak periods. As a result, the company estimates that annual electricity bills for cooling might be reduced by approximately 45%.

21. Launch of mass production of the fastest-charging EV platform, reducing recharge times to those approaching gasoline refuelling

Megawatt fast-charging technologies could remove a barrier to large-scale electrification of road transport. Bringing charging speeds in line with refuelling speeds can increase the appeal of battery electric cars to consumers, provided ultra-fast charging infrastructure are deployed. In March 2025, BYD, a Chinese carmaker, set a new benchmark for charging speed with its Super-e platform, which it claims can provide around 400 km of range in 5 minutes. This leap was made possible by next-generation silicon carbide power chips, all-liquid-cooling, and a 1 000-volt architecture, which allows for coupling with 1 MW charging.

22. A new grid-stabilising unit uses supercapacitors to deliver active and reactive power for voltage and frequency support

Supercapacitor-enabled grid-stabilisation systems deliver ultra-fast power support for voltage regulation and short-term frequency response, providing stability services in renewable-heavy power systems. In December 2025, Siemens Energy, a German equipment supplier, started operation of an E-STATCOM pilot plant in Germany, which uses supercapacitors to provide both voltage and frequency stabilisation for the first time. It combines short-duration active power capability (in the order of 200 MW pulse output) with approximatively 300 MVAr reactive support, using a grid-forming control strategy and supercapacitor energy storage, which compensates for short-term load fluctuations and thus provides grid inertia. In parallel, Hitachi Energy, a global equipment supplier headquartered in Switzerland, will commission two E-STATCOM systems at Wendlingen and Oberjettingen in Germany with TransnetBW, a German TSO.

23. Real-time methane emissions detection equipment to curtail methane footprint is being rolled out worldwide

Advanced drone-based methane-detection tools provide fast, precise emissions monitoring across large sites, enhancing the ability to identify leaks and cut methane emissions. TotalEnergies, a French oil company, has further refined its Airborne Ultralight Spectrometer for Environmental Applications (AUSEA) system to make it suitable for multiple geographies, and announced successful deployment in 2025. Adding more drone autonomy, tailored data processes and automation has made near-real-time methane emissions monitoring across diverse sites possible globally. The system was first used in 2017 and has since been further developed to adapt the sensor, flight protocols and data-processing algorithms to a wider range of climates, terrains, industrial setups and regulatory contexts.

24. Commercial deployment of sodium-ion batteries begins in multiple sectors

Sodium-ion batteries could diversify battery supply chains and reduce exposure to lithium price volatility and critical mineral risks, as well as supporting improved EV performance in cold climates. In March 2025, Hina, the first company to have supplied sodium-ion batteries for electric cars, in 2023, released their second-generation sodium-ion batteries. In April 2025, CATL also released its second-generation sodium-ion battery products, and established Naxtra as its dedicated sodium-ion battery brand. Naxtra products are offered in passenger-vehicle power-battery formats and as a 24 V integrated battery solution for heavy trucks, with reported specific energy of 175 Wh/kg and an operating temperature range of -40°C to 70°C. In December 2025, CATL confirmed plans for commercial-scale deployment across multiple sectors from 2026, including battery swap systems, passenger vehicles, commercial vehicles and energy storage. In parallel, BYD launched a mass-produced sodium-ion battery counterbalance forklift, targeting industrial applications requiring reliable performance in cold conditions (reported operating range: -40°C to 60°C).

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

This section presents selected highlights from 2025 in an important but often under-represented area: investments in new facilities for R&D and testing. The five examples cover new infrastructure that is being developed for different technologies to reduce costs for innovators and generate comparable performance results to inform future funders.

TRL

Cross-cutting

Announcement of a new computing and AI research platform for energy research

TRL

CCUS

New public CO2 capture and utilisation test bed inaugurated

TRL

Hydrogen

Construction of a new public R&D test centre focused on hydrogen technologies begins

TRL

Industry

New glass furnace fires up at test centre

TRL

CCUS

Multi-technology DAC innovation centre starts operation

25. Announcement of a new computing and AI research platform for energy research

In November 2025, the US government announced the Genesis Mission to build an integrated, AI-driven scientific discovery platform that will involve government-owned supercomputers, data held by national laboratories, automated experimentation and emerging quantum technologies. While the Mission spans many domains, its strongest near-term relevance is in energy innovation: the platform aims to dramatically accelerate R&D cycles in advanced nuclear (fission and fusion), grid technologies, critical materials discovery, energy-relevant chemistry, and next-generation clean-energy manufacturing. By compressing the time from hypothesis to validated result, AI tools such as this could help researchers accelerate innovation in energy-relevant technology areas.

26. New public CO_2 capture and utilisation test bed inaugurated

In 2025, the Korea Research Institute of Chemical Technology, a public research institute, established a test centre to validate key CCUS technologies with the equivalent of USD 15 million. Companies including GS Caltext, a Korean energy company, will be able to use the facilities to test the capture CO_2 and its conversion to chemicals. The availability of publicly accessible testing facilities can accelerate innovation in carbon management technologies.

27. Construction of a new public R&D test centre focused on hydrogen technologies begins

In September 2025, construction began at a new Innovation and Technology Centre for Hydrogen in Germany. The centre, which is funded with about USD 310 million from the German government, will support companies in the road, maritime and aviation transport sectors by providing specialised testing and certification not yet available on the market. It will provide small- and medium-sized businesses with access to state-of-the-art laboratories, test benches and development platforms, and also includes a hydrogen technology training centre for vocational academies and universities.

28. New glass furnace fires up at test centre

In June 2025, Glass Futures lit the world's first multi-fuel hybrid furnace for the global glass industry to use for innovation and testing. The 30 tonne per day furnace, approximately 5 to 30 times smaller than commercial-scale units, is the world's first multi-fuel hybrid furnace, and will be used in international trials aimed at creating sustainable, lower-carbon glass and other materials. Glass Future's USD 70 million Global Centre of Excellence in glass manufacturing has been supported by USD 20 million from the UK government and over USD 10 million from the Liverpool city region, as well as funding for projects on materials innovation, electrification, fuel innovation, digitalisation and AI, and carbon capture.

29. Multi-technology DAC innovation centre starts operation

In August 2025, Deep Sky, a Canadian start-up, commenced operations at Project Alpha – a multi-technology facility in Canada for operating direct air capture (DAC). Supported by the Government of Alberta and Breakthrough Energy, a private funder and advocacy group, the centre has purchased DAC units from technology providers from around the world, and has so far commissioned units – from Mission Zero Technologies, Skyrenu, and Airbus – that are now capturing and storing CO_2 in a dedicated geological site underground. Credits to be generated from these installations have been pre-sold to Microsoft and RBC. Operations began only 1 year after the start of construction, a milestone highlighted in The State of Energy Innovation 2025.

The IEA Races to First in energy innovation

To celebrate, track, encourage and communicate progress towards a selection of the outstanding scale-up challenges, we defined 18 Races to First in Energy

Innovation in The State of Energy Innovation 2025. In this section, we present selected updates from the past year, including existing projects moving to the next phase and new entrants joining the races.

These are key milestones towards which we know of innovators working hard to stay on track and most of which we believe are achievable by around 2030 with sustained policy support. 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.

For each race, several projects and companies are currently vying to achieve the milestone first, often with competing technology options. Winning the race represents much more than technical development; it shows that innovators are also navigating the non-technical obstacles that stand in their way, which deserves equal recognition and support from policy makers and other actors.

Each race passes through four phases:

- **Phase 1:** Testing at a smaller scale or in different configuration
- **Phase 2:** Raising funds and preparing for next phase
- **Phase 3:** In construction and could meet criteria
- **Finish line:** Meets criteria

First carbon-free flight

- **Objective**: A safe continuous flight of 1 000 km or more with no propulsion from a carbon-containing fuel.
- **Criteria**: Aircraft capable of carrying 20 passengers or equivalent.

Update: Phase 2

- 2024: ZeroAvia, a **US** start-up, and KLM, a **Dutch** airline, announced plans for a demonstration of a large regional turboprop with hydrogen-electric propulsion. (TRL 5).

First freight ship powered by a carbon-free fuel

- **Objective:** 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.
- **Criteria:** A vessel with a deadweight tonnage of at least 100 000 tonnes. Engine main power of at least 10 MW.

Update: Phase 3

- 2025: Everllence (formerly MAN Energy Solutions), a **German** engine maker, announced that its first 60 bore (17 MW) engine on a 200 000 deadweight tonnage bulk carrier is due for delivery to a **Japanese** joint venture in early 2026. (TRL 6).

Update: Phase 2

- 2025: **Swiss** engine maker WinGD finished the construction of its first 52 bore (about 13 MW) engine and started installation of a 45 000 cubic metre (about 29 000 DWT) ammonia carrier ordered by EXMAR, a **Belgian** shipping company. The ship is expected to start operation in 2026. (TRL 6).
- 2025: J-Eng, a **Japanese** engine maker, finished the testing of its first 50 bore (about 12 MW) ammonia dual-fuel engine, to be fitted to a gas carrier in 2026. (TRL 6).

First repeatedly deployed nuclear small modular reactor (SMR) or micro reactor

- **Objective:** Successful commissioning of three or more installations at different sites of the same nuclear reactor design, including in two different countries.
- **Criteria:** 300 MW_e or less. Can be for terrestrial electricity or heat supply purposes.

Update: Phase 1

- 2025: GE Vernova Hitachi plans to deploy a boiling water SMR design, the BWRX-300, in several countries. Major advances were made in 2025 in **Canada** (licence to construct the first BWRX-300), the **United States** (USD 400 million grant to an utility to assist in the construction of a BWRX-300), the **United Kingdom** (progress in the United Kingdom's Generic Design Assessment), **Sweden** (Vattenfall selected GE Vernova as a potential supplier), **Poland** (licensing agreement to use BWRX-300 design for one unit) and **Estonia** (Fermi Energy started site selection process).
- 2025: Rosatom, a state-owned **Russian** nuclear company, is constructing its first land-based RITM-200N SMR for commissioning in 2028. In **Uzbekistan**, preparatory work is underway for two RITM-200N units at a new integrated site. (TRL 8).
- 2025: Rolls-Royce, a **UK** engineering firm, was selected by the UK government to supply the first UK SMR if it receives regulatory approval. The company also signed early works agreement with a Czech utility, and has been selected as a potential supplier by a Swedish utility.

The first solid-state cooled building

- **Objective:** Use of solid refrigerant technologies as the main means of air conditioning.
- **Criteria:** Multioccupancy residential or tertiary building.
- **Period:** Each day over a period of one summer month.
- **Other:** Only technologies using the caloric effect are included, as these have the largest potential for achieving high efficiencies.

Update: Phase 2

- 2025: **UK** start-up Barocal has been raising funds and expanding. In 2026 Barocal will start testing the third generation of its barocaloric cooling solution, promising even better performance than previous year's tests. (TRL 5).

Update: Phase 1

- 2025: **German** companies Magnotherm and The Colony conducted a successful joint feasibility project using magnetocaloric space cooling, which marks the first recorded time that magnetocaloric space cooling has been tested for an extended period in realistic settings in a building. (TRL 6).
- 2025: Hong Kong University of Science and Technology, **China**, developed the first elastocaloric cooler on the kilowatt scale. (TRL 5).

The first large-scale near-zero emissions cement plant

- **Objective:** Cement produced with 40 to 125 kg CO_2-eq per tonne and sold or otherwise transferred for commercial use in load-bearing applications.
- **Criteria:** 750 000 tonnes or more. Cumulative over 12 consecutive months. 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.

Update: Phase 3

- 2025: Following a funding agreement with the UK government, Heidelberg Materials, a **German** cement company, took a final investment decision to build a full-scale CO_2 capture facility at a **UK** cement plant by 2029. The project will capture around 800 000 tonnes of CO_2 per year, making it the first cement facility with such low emissions. (TRL 7).

Update: Phase 1

- 2025: EcoCem, an **Irish** company, took an investment decision to build a 300 000 tonne facility in **France** for low-clinker, high-filler cement, targeting operation by 2026. (TRL 7).
- 2025: As of October 2025, a **Norwegian** cement plant operated by Heidelberg Materials, a **German** company, captures around 400 000 tonnes of CO_2 per year, equal to about half of the plant's emissions, which is not yet sufficient to meet the criteria. (TRL 9).
- 2025: Sublime Systems, a **US** start-up, agreed an offtake agreement with Microsoft for 620 000 tonnes of cement over a 6-9-year period from their proposed 30 kt/yr demonstration project of an electrolytic technology. However, this demonstration project was paused after the cancellation of a federal grant. (TRL 5).

First aluminium plant with very low direct emissions

- **Objective:** Primary aluminium produced with direct emissions from smelting of 0.2 t CO_2-eq per tonne or less.
- **Criteria:** 2 000 tonnes or more. Cumulative over 12 consecutive months. Any CO_2 storage must be verifiable according to a dedicated regulatory regime. Direct emissions from smelting included in the emissions intensity calculation.

Update: Phase 2

- 2025: Elysis, a **Canadian** joint venture, also announced in 2025 the start-up of 450kA inert anode cells. This is a significant step up to the most commercial cell scale (the demonstration plant being built for 2027 plans to use ten 100kA cells). (TRL 7).

Update: Phase 1

- 2025: GreenCap Solutions, a **Norwegian** start-up, began a 1-year demonstration of its CO_2 capture technology at a primary aluminium plant operated by Hydro, a Norwegian company. The technology uses a solid sorbent and physical adsorption to capture very low CO_2 concentrations. (TRL 5)

First fast-cycling underground hydrogen storage facility

- **Objective:** More than three injection and withdrawal cycles achieved within a year, and the withdrawn hydrogen transferred for use.
- **Criteria:** 200 GWh storage capacity or higher. Facility in operations for 6 months or more. Injections and withdrawals of 10 GWh or more each.

Update: Phase 3

- 2025: The 300 GWh ACES Delta project in the **United States** began injecting hydrogen into underground salt caverns to establish the cushion gas required ahead of commissioning. (TRL 6)

Update: Phase 1

- 2025: RWE, a **German** energy company, took a final investment decision on the 115 GWh Epe-H2 salt cavern storage in Germany. Commercial operation is targeted for 2027. (TRL 6)
- 2025: The **EU**-funded HyPSTER consortium of European companies and public institutes announced the successful completion of 4 months of hydrogen storage testing in salt caverns in **France**, involving approximately 100 injection-withdrawal cycles under varying conditions of pressure and cycling speed. (TRL 6)

First refinery-scale next-generation sustainable aviation fuel plant

- **Objective:** Sale of aviation fuel whose energy content derives entirely from electricity, lignocellulosic biomass, and/or algae to airline operators or their fuel suppliers.
- **Criteria:** 100 000 tonnes of kerosene equivalent. Cumulative over 12 consecutive months. Fuel must be of a type that can be blended 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.

Update: Phase 3

- 2024: **China** Energy Engineering Group, a state-owned company, began construction of a 100 000 tonne synthetic aviation fuels plant in Heilongjiang province, to be operational in 2027, combining biomass gasification, low-emissions hydrogen and Fischer-Tropsch synthesis. (TRL 5)

Update: Phase 1

- 2025: Infinium began construction of the Project Roadrunner in the **United States**, for a 23 000 tonne synthetic aviation fuel plant using waste CO_2 and Fischer-Tropsch synthesis. (TRL 7)

First large-scale long-duration storage battery

- **Objective:** 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.

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

Update: Phase 1

- 2025: **China** Huaneng Group, a state-owned electricity company, commissioned the world's largest vanadium flow battery in Xinjiang province, with 1 000 MWh capacity designed to fully discharge in 5 hours. (TRL 9)
- 2025: Ore Energy, a **Dutch** start-up, connected a pilot iron-air battery to the grid, aiming to evaluate its performance over repeated multi-day charges. (TRL 7)

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

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

Update: Phase 1

- 2025: Mazama Energy, a **US** start-up, began a super-hot rock testing step at its pilot site in Newberry, Oregon, before proceeding to 15 MW in 2026. (TRL 6)

The first commercial-scale low energy intensity ammonia production

- **Objective:** Ammonia produced from water with an energy intensity of less than 25 GJ of energy input per tonne of ammonia produced.
- **Criteria:** 100 000 tonnes or more globally using a single technology design. Cumulative over 12 consecutive months. 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.

Update: Phase 1

- 2025: Atvos, a **Brazilian** bioenergy company, announced plans for a 20 000 tonne facility using electride catalyst technology for low-temperature, low-pressure ammonia synthesis from Tsubame BHB, a **Japanese** start-up. (TRL 5)
- 2025: NitroVolt, a **Danish** start-up, scaled its lithium-mediated ammonia synthesis process from gram-per-day to kilogram-per-day levels. (TRL 3)

The first commercial 30% efficient solar photovoltaics

- **Objective:** Production of a solar module design with a nameplate conversion efficiency of 30% or more.
- **Criteria:** 100 MW or more. Cumulative over 12 consecutive months.

Update: Phase 1

- 2025: Yanhe Technology, a **Chinese** start-up, completed and commissioned a 100 MW fully automated perovskite solar cell production line. (TRL 6)
- 2025: GCL, a **Chinese** energy technology company that has commissioned 100 MW of cell production capacity, reported a 29.51% efficiency perovskite-silicon tandem module. (TRL 6)
- 2025: Renshine Solar, a **Chinese** company with a 150 MW perovskite production line, and Nanjing University, a Chinese public university, reported a conversion efficiency of 30.1%, certified by Japan's Electrical Safety and Environment Technology Laboratories. (TRL 6)
- 2025: LONGi, a **Chinese** solar manufacturer, reported a 33% efficiency crystalline silicon-perovskite two-terminal tandem solar cell, a new record for large-area tandem cells certified by the US National Renewable Energy Laboratory. (TRL 6)
- 2025: Fraunhofer ISE, a **German** public research institute, reported a 30.6% efficiency perovskite-silicon tandem cell that demonstrated the suitability of industry standard TOPCon silicon cells for tandem designs. (TRL 6)
- 2025: 3SUN, an **Italian** solar manufacturer, and CEA, a **French** public research institute, reported a 30.8% efficient 9 cm² screen-printed tandem cell, a 27.3% efficient 100 cm² cell, and less than 1% efficiency loss after 9 months outdoor tandem cells. (TRL 6)

The first electric vehicle with a solid-state battery

- **Objective:** Serial production of a vehicle on the market powered entirely by a fully solid-state battery.
- **Criteria:** 10 000 or more at least 4-seater vehicles or equivalent. Cumulative over 12 consecutive months.

Update: Phase 2

- 2025: BYD, a **Chinese** carmaker, confirmed plans to roll out vehicles with solid-state batteries in 2027 and to begin mass production from 2030. (TRL 6)
- 2025: Toyota, a **Japanese** carmaker, announced plans to launch its first all-solid-state battery-powered vehicle by 2028. (TRL 6)

Update: Phase 1

- 2025: QuantumScape, a **US** start-up, tested its solid-state batteries in a motorcycle. (TRL 6)

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

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

Update: Phase 3

- 2025: **Swedish** firm Stegra's electrolytic hydrogen plant in Boden, Sweden, is being constructed, aiming to begin operations in 2026 and ramp to a full scale of 2.5 Mt of steel produced via direct reduction in 2027 or 2028. In October 2025, Stegra opened a new financial round aiming to cover a funding gap. (TRL 6)
- 2025: The Hebei Bishi steel plant in Inner Mongolia, **China**, started construction of a facility using a hydrogen-based direct reduction technology, aiming to be online in 2028 at a scale of 2 million tonnes. This seems to be a delay from an original timeline which would have had construction finish in 2025. (TRL 6)

Update: Phase 1

- 2025: HyIron, a **German** company, completed construction of a 15 000 tonne pilot plant in **Namibia** using hydrogen-based direct reduced iron technology and with scope for future expansion. (TRL 6).
- 2025: Electra, a **US** start-up, started construction of 500 tonne demonstration facility using a low-temperature electrochemical method. (TRL 5).
- 2025: Boston Metal, a **US** start-up, commissioned a multi-inert anode molten oxide electrolysis pilot cell that produced steel. (TRL 5).

The first large-scale multi-source CO_2 storage hub in operation

- **Objective:** A single CO_2 storage site stores CO_2 from at least three different sources.
- **Criteria:** 100 000 tonnes of CO_2 or more captured per source. Cumulative over 12 consecutive months. Must be verifiable according to a dedicated regulatory regime.

Update: Phase 3

- 2025: **US** company Tallgrass Energy started operating the Trailblazer CO_2 pipeline, a retrofitted 392-mile natural gas line linking ethanol plants in Nebraska and Iowa to a permanent storage site in Wyoming. MAAPW, an ethanol producer, became the first customer to deliver CO_2 to the Trailblazer pipeline. (TRL 9)
- 2025: Northern Lights, a joint venture between Equinor, Shell, and TotalEnergies, received the first CO_2 shipment captured from a cement plant in **Norway,** at a newly constructed terminal, and injected it under the **Norwegian** seabed. There are three other sources lined up to supply CO_2 from 2026 (430 000 and 800 000 tonnes) and 2029 (350 000 tonnes). (TRL 9)
- 2025: Eni, an **Italian** oil and gas company, started construction on a 5 million tonne CO_2 transport and storage hub in depleted gas fields off the **UK** coast**.** Construction also started on CO_2 capture at two of the associated CO_2 sources that aim to be operational from 2029 (800 000 and 370 000 tonnes, respectively). (TRL 8)
- 2024: Northern Endurance Partnership, a joint venture between BP, Equinor and Shell, started construction on a 4 million tonne CO_2 transport and storage hub in a saline aquifer off the **UK** coast**.** Construction also started on CO_2 capture at one of the associated CO_2 sources that aims to be operational from 2028 (2 million tonnes). (TRL 9)

Biochemical improvement of CO_2 assimilation

- **Objective:** 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.
- **Criteria:** 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.

Update: Phase 1

- 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.

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 2025 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 2025

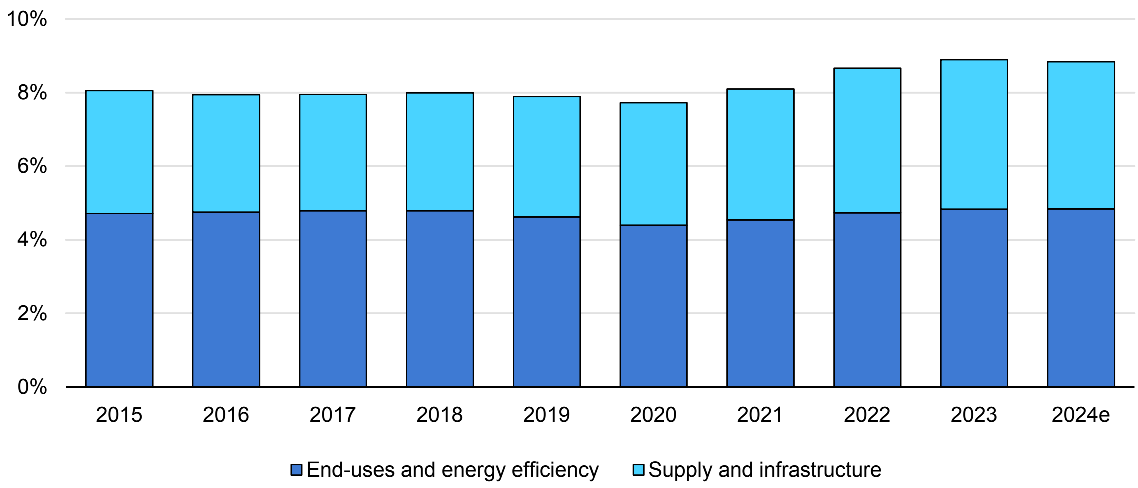
Award and criteria	2025 winner(s)	Country
Hydrogen TCP Awards of Excellence 2025 for hydrogen innovations and technologies for hard-to-decarbonise sectors and sustainable fuels.	NOVELIS HyNet Industrial Fuel Switching for successfully completing the United Kingdom's **first full-scale hydrogen fuel switching demonstration** in the aluminium industry.	United Kingdom
	COSMHYC DEMO for **creating of a hydrogen refuelling station** capable of refuelling light-duty utility hydrogen vehicles, passenger cars, as well as heavy-duty vehicles and refuse collection vehicles at both 350 and 700 bar pressure.	France
International Smart Grid Action Network (ISGAN TCP) Award of Excellence 2025 for solutions for enhanced grid operation.	Energy Networks Association's Open Networks Programme for **transition to Distribution System Operation (DSO)**, enabling local network operators to manage supply, demand and constraints more effectively.	United Kingdom
District Heating and Cooling TCP 2025 Awards for research excellence in district energy (Best papers).	• N. Kozlowska, A. Lefebvre, J. Jacquemin and P. Dewallef, "Optimizing a Multi-Vector Energy System with Geothermal-Powered District Heating", University of Liège.	Belgium
	• M.-R. Kolahi and M. Patel, "Optimizing the Next Generation of District Heating and Cooling Systems While Ensuring Reliable Domestic Hot Water Supply", University of Geneva.	Switzerland
	• H. Hoes and J. Pauwels, "A 5th Generation District Heating and Cooling Network (5GDHC) Driven by Shallow Geothermal: Economic Analysis and Geohydrological Modelling for Comparison with an Individual System", Terra Energy.	Belgium
	• J. E. Thorsen, O. Gudmundsson, M. Tunzi and M. Brand, "Improved District Heating Return Temperatures by Cascading Concepts", Danfoss.	Denmark

	• Q. Yang, F. Saba, M. Orio, M. Santiano, E. Audrito, R. Salenbien and M. Tunzi, "Data Pre-processing Methods Enhancing Heat Cost Allocator Measurement Usability", Danish Technical University, VITO / EnergyVille, National Metrology Institute of Italy.	Belgium, Denmark and Italy
Solar Power and Chemical Energy Systems (SolarPACES TCP) 2025 Awards for contributions to the deployment of concentrated solar power (CSP) technology.	**Technology innovation award:** ODQA and KTH Royal Institute of Technology's Innovative High-Temperature Air-Based Integrated CST for Flexible Renewable Heat for **pioneering work advancing high-temperature air-based industrial heat**, involving successful integration of ODQA's rotary air receiver and KTH's high-temperature radial flow packed-bed thermal energy storage solution, proven at pilot scale for industrial hot-air applications.	United Kingdom and Sweden
	Technology implementation award: Cosin Solar's 50 MW Delingha Concentrated Solar Power plant for **achieving long-term stable operation** of CSP technologies, including through the **use of advanced machine-vision based heliostat control,** resulting in tracking accuracy 66% higher than industry standard, along with **dynamic receiver management,** enabling superior generation in cloudy conditions.	China
	Lifetime Achievement award: • Mark Mehos for **work on quantification of operational and economic value of CSP** with thermal storage in renewable-heavy grid scenarios. • Craig Turchi for **major innovations in heat transfer, hybrid systems, and techno-economic modelling**, integrating advanced cycles such as supercritical CO_2 into widely adopted industry analysis tools like the US National Renewable Energy Laboratory's System Advisor Model and SolTrace	United States
Mission Innovation Net Zero Industries Awards 2025	**Young Talents award:** Saravanan Janakiram (Aqualung Carbon Capture) for u**se of coated membranes to passively separate different gas molecules**, allowing to cost-effectively capture carbon even at small scale (<100,000 TPA) and at low CO_2 concentration.	Norway
	Female Innovators award: Christine Gabardo (Co-founder and CTO CERT Systems Inc) for **scale-up of CO_2 electrolysis** from academic research to industrial scale, turning waste CO_2 into renewable chemicals and fuels.	Canada
	Outstanding Projects award: Helios Project Limited's Helios Cycle for development of **novel method for iron ore reduction** using sodium-based process with zero direct emissions.	Israel
	Top innovation for industrial electrification: Polar Night Energy's Sand Battery for the development of an **industrial-scale, high-temperature thermal energy storage system** using sand, sand-like materials, or industrial by-products as its storage medium.	Finland

Chapter 2. Tracking spending trends

Money is a key input to innovation, which always involves putting capital at risk in the service of uncertain future returns. Most funders of energy innovation do so across a portfolio, in the expectation that successful new technologies will more than pay for the more disappointing projects, in terms of revenue, environmental protection or technical spillovers that spur unanticipated advances. The higher risks of investing in innovation compared to other energy system assets has traditionally made this an area where the public sector plays an important role in sharing the risks with companies seeking a long-term competitive advantage. There is no shortcut to innovation that does not carry the possibility of failure, and no shortcut to long-term competitiveness that does not involve innovation. This chapter presents the latest data on spending on energy innovation by the public and private sectors separately, as well as the trends in venture capital (VC) funding of innovative start-ups.

Energy R&D expenditures as shares of total global R&D expenditures, 2015-2024e



Notes: Includes public and corporate R&D. Early-stage VC funding data is used to estimate the R&D spending of energy start-ups. 2024e: estimated. Total global R&D expenditure in 2024 is estimated based on World Intellectual Property Organization analysis.

Sources: IEA (2025), Energy Technology RD&D Budgets and analysis based on data from OECD (2025), Cleantech Group (2025), Crunchbase (2025) and WIPO (2025).

Spending on energy innovation is rising faster than total R&D across all sectors, according to the latest reported data. Globally, roughly 9% of all R&D spending by the public and private sectors is dedicated to energy.[4] After remaining steady in the period from 2015 to 2020, this share has risen by almost one percentage point. We judge that this rise was mostly related to R&D for supply-side technologies.

Three types of spending tracked in The State of Energy Innovation

Public R&D. Public spending on R&D is essential to energy innovation, funding projects that the private sector is unable or hesitant to support. It also guides researchers towards scientific and technical challenges that are relevant to delivering policy priorities. In general, whether early-stage R&D or larger-scale demonstration projects, public funds target the projects with the highest-risk, most long-term payoffs. This makes governments central to the emergence of disruptive technologies that create new sectors of activity and drive faster economic growth. While governments have a range of tools for allocating capital to innovators, most public R&D spending is via grants to research institutes, consortia or companies undertaking projects. Funding for energy innovation is typically conditional on private sector co-funding, calibrated to maximise private sector spending on key technology challenges at the lowest public cost.

- In this chapter, the public energy R&D data come mainly from the IEA Energy Technology RD&D Budgets database, a compilation of submissions each year from IEA Member governments and Brazil. As of the end of 2025, data are available for 2024 and several national estimations for 2025 have been received. It mostly covers grant funding. Data on the allocation of concessional debt and tax breaks for energy innovation are scarce.

Corporate R&D. Companies generally spend a fraction of their revenue on research to try to maintain a competitive advantage. Most of this spending goes to troubleshooting technical challenges with existing products, and incremental improvements to equipment on the market. Younger companies are more likely to spend a higher share of their research budget on disruptive technologies that could displace incumbents and lead to rapid scale-up. More mature companies may seek to use research to defend their territory, with the largest firms able to also allocate a share of revenues to more radical technologies and first-of-a-kind projects.

- In this chapter, data on corporate R&D are taken from the annual financial statements of companies, mostly listed companies. Disclosed R&D budgets are not itemised by technology area in public filings, so assumptions must be made about the links between companies' market activities and their R&D focus areas.

Venture capital. VC funding is from investors to young companies in the form of equity, i.e. the investor receives a share of the companies' stock. In addition, VC

[4] For simplicity in this report, R&D includes demonstration. The data are therefore inclusive of all reported RD&D.

investors often play an active role in honing the start-up's strategy and business capabilities. This model of funding is suited to innovative start-ups with the potential to grow quickly into major firms or be sold for large sums. These start-ups are often spin-offs from the most promising and potentially disruptive publicly-funded research programmes. Not only does VC funding fill important gaps between public, institutional and corporate funding, it is also a good indicator of the health of a national risk-tolerant innovation ecosystem. VC funding can be split into two phases: early-stage funding, which allows innovators to experiment and test technologies while building a business; and growth-stage funding, which is allocated to start-ups that continue to show significant promise after the early stage and need much larger sums to scale up via demonstrations or initial manufacturing facilities. In this chapter, the two phases are shown separately, given the much closer relationship between early-stage funding and technology innovation effort.

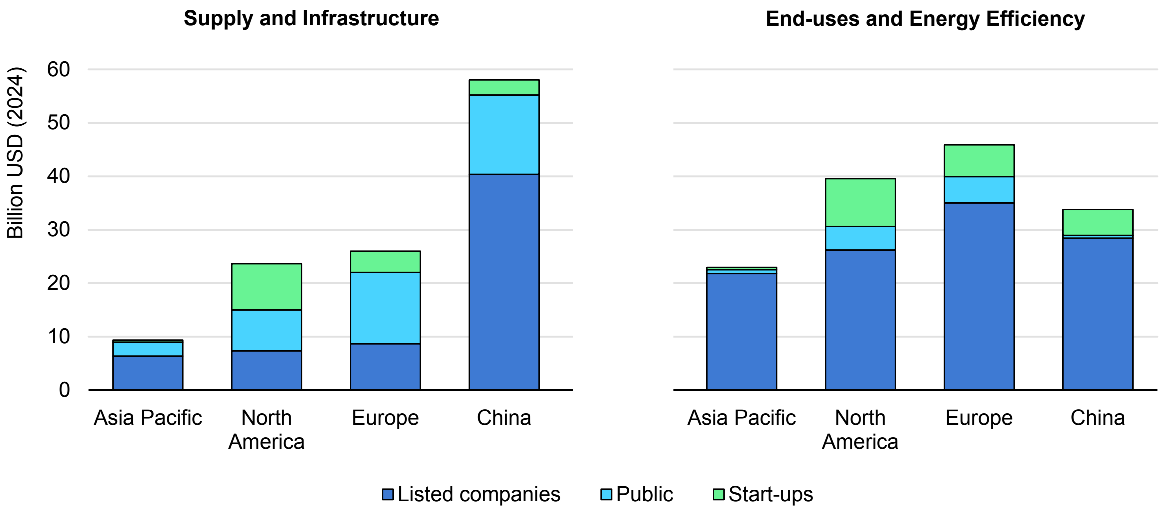
- In this chapter, VC data are based on classification and analysis of commercial datasets of deals and start-ups.

In recent years, both public and private energy R&D have been rising faster than GDP. In 2024, total public related energy R&D expenditure stood at USD 55 billion, a 70% increase in real terms from 2015. However, indications of 2024 and 2025 budgets suggest a pause in the growth trend since 2016, partly linked to funding cuts in the United States and cycles of budget allocation in Europe. R&D expenditure by corporations operating in energy-related sectors continued to grow in 2024, reaching over USD 160 billion. However, growth was slower than in any year since 2015, possibly due to higher costs of capital faced by firms in 2023 and 2024.

Energy-related VC appears to be in a transition phase. Overall investment levels fell in 2025 for the third straight year, but there is notable growth and dynamism in several technology areas that indicate continuing investor appetite for energy innovation risk. Data explored in this chapter show that while fewer start-ups have been able to raise funding – partly due to some investors reallocating their portfolios towards artificial intelligence (AI) – the decline is also related to the end of a major cycle of funding for electric mobility. Excluding electric mobility, energy-related VC activity has not shrunk, unlike many other VC areas such as biotechnology, fintech and agriculture.

Caution must be taken when aggregating across funding types, regions and technologies. Firstly, summing different sources of spending on an equal basis does not fully reflect the contribution of public R&D and VC to funding the most high-risk and potentially disruptive research. It can also mask regional differences, for example in the importance of VC. Among major regions, North America has more balanced shares of the three types of funding for energy supply and infrastructure technologies. Corporate R&D plays a larger role in all major regions for end-use and energy efficiency technologies, driven by the spending of automotive firms on vehicle efficiency and electrification. These firms have some of the world's largest R&D budgets across all sectors.

Distribution of average yearly energy innovation spending, 2021-2025



Notes: Chart provides an overview of the order of magnitude. Data limitations mean that sectoral classifications between different funding sources cannot be precisely mapped. Some countries' public R&D cannot be allocated by sector, including a large share of China's funding, nor separated precisely from corporate R&D, which is the case for some Chinese state-owned enterprises possibly covered in both categories. Includes growth-stage energy VC as well as early-stage. For end-use and energy efficiency, an attempt has been made to estimate the energy-related portion of R&D spending of corporations in sectors such as buildings, heavy industry and transport.

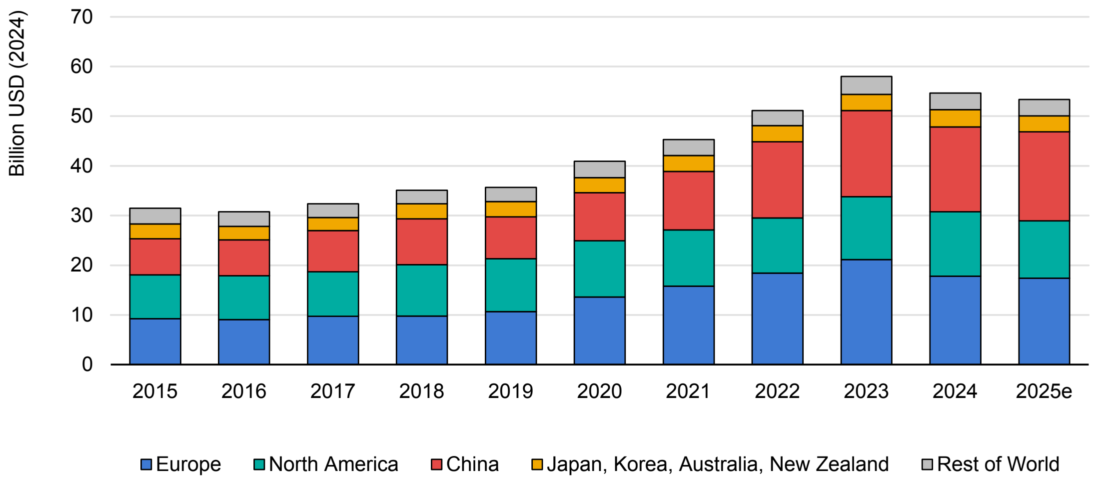
Source: IEA (2025), Energy Technology RD&D Budgets database.

Public R&D

Annual government spending on energy R&D globally has faltered after 7 years of sustained growth, in which spending rose on average by 10% per year. For IEA Member countries, this took it above the previous high point for energy R&D spending in 1980 in real terms, and spending remains high at USD 55 billion. We estimate that 78% of the spending in 2024 went to low-emissions technologies.

Two main reasons for the current pause in the public R&D growth trend are visible in the data. The first is a dip in annual spending on energy R&D from the EU budget, following steady growth up to a peak in 2023. This peak relates primarily to the way that funds worth USD 9 billion were awarded to demonstration projects under the EU Innovation Fund in 2023 and allocated retrospectively to that year once the final commitment was signed. The same process may push up the 2024 and 2025 values in future. The second reason is a reduction in 2025 of federal energy R&D funding in the United States. This too might be a temporary effect, with reallocation of some funds to new innovation priorities.

Government spending on energy R&D, 2015-2025e



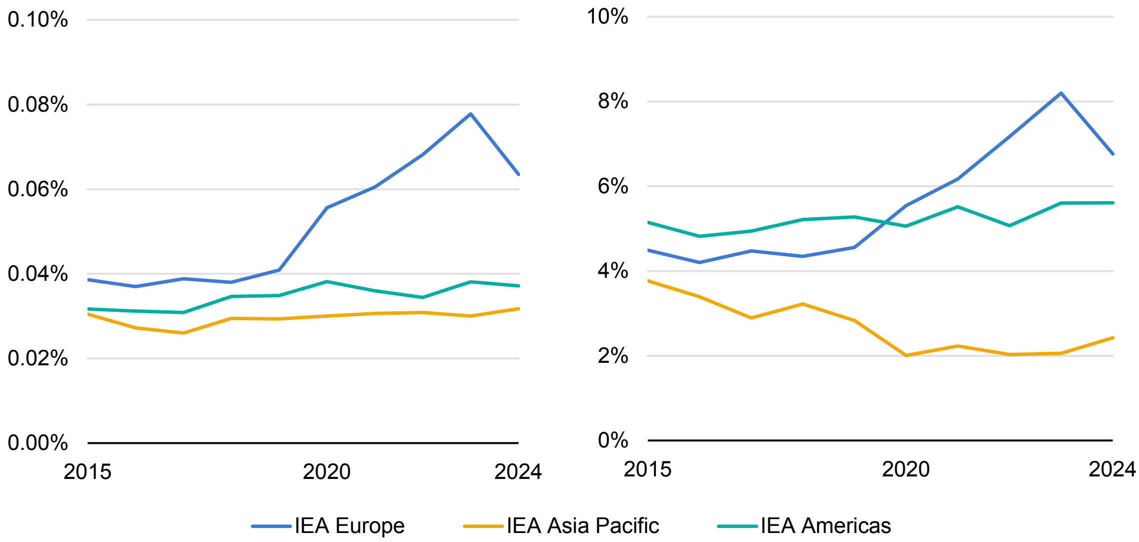
Notes: Includes spending on demonstration projects (i.e. RD&D) wherever reported by governments as defined in IEA documentation. 2025e: estimated. As of the end of 2025, data are available for 2024 and several national estimations for 2025 have been received. State-owned enterprise funds comprise a significant 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 (2025), Energy Technology RD&D Budgets database.

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 to boost energy security after the oil crisis. In 1980, IEA Member countries spent 0.1% of GDP of energy R&D, with a big chunk going to nuclear research. Today, spending is growing as a share of GDP, but stands at less than 0.05%. Given today's converging energy policy challenges – energy security, critical mineral supplies, competitiveness, climate change and energy access – there are strong reasons for governments to once again aim to reach 0.1% of GDP. Some European countries – Spain, France and Belgium – are already at this level when including the additional spending that they route via the European Union budget, and Norway, which is not an EU member state, averaged 0.09% in 2021-2024. Our estimate of China's public energy R&D spending, which has grown to a similar level to that of Europe, would place it around 0.07% of China's GDP.

Among IEA Members, public energy R&D spending has also risen as a share of total public R&D spending. This is largely due to a step-up in Europe since 2020, from less than 4% to almost 5%, a value that places it on a par with the United States. However, 5% remains lower than our estimate of the share of energy in total public and private R&D combined. At first glance, this implies that governments place less importance on energy R&D than the private sector.

However, much of the difference might be explained by a much higher share of government R&D spending being directed towards basic research rather than applied research.

IEA Member countries' public energy R&D spending as a share of GDP (left) and total public R&D (right), by region, 2015-2024



Notes: Total public R&D does not include demonstration spending, unlike energy public R&D spending; the impact of this misalignment on the ratio is not significant. IEA Europe includes funding from the EU budget, with GDP adjusted accordingly.
Sources: IEA (2025), Energy Technology RD&D Budgets database and analysis based on data from OECD (2025).

Top ten public energy R&D spenders as a share of GDP among IEA Member countries, 2022-2024

Country	Public energy R&D as a share of GDP, 2022-2024	Share of global energy R&D spending, 2022-2024
Spain	0.13%	4%
France	0.11%	7%
Belgium	0.11%	1%
Austria	0.10%	1%
Finland	0.09%	<1%
Norway	0.09%	1%
Sweden	0.07%	1%
Germany	0.07%	6%
Czech Republic	0.07%	<1%
Portugal	0.07%	<1%

Note: For EU member states, figures in this table include an estimate of the country's contribution to EU-level energy R&D spending. Values excluding EU spending are provided in the Annex.

Public R&D spending targets different parts of the innovation process

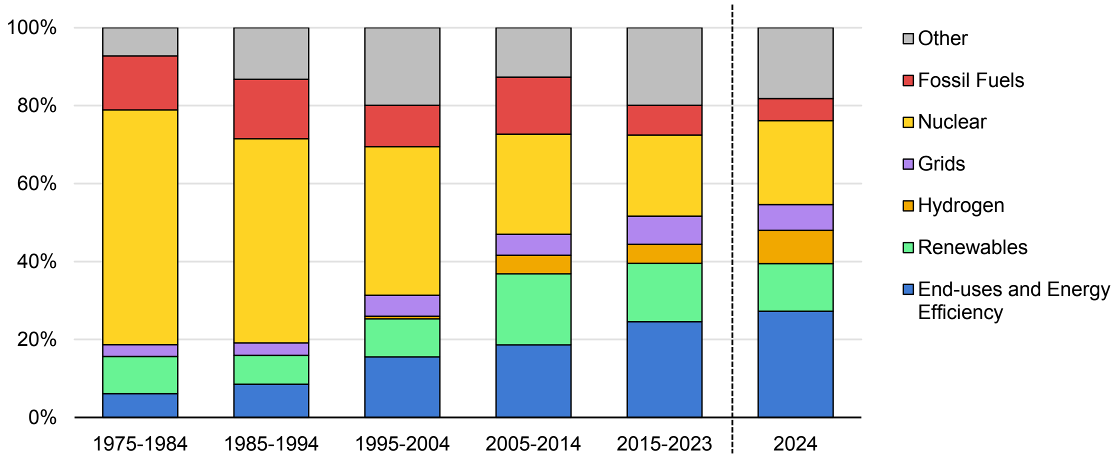
Funding needs to evolve with technology maturity. Along the innovation journey for an energy technology, funding for experimental research gives way to spending on pilot facilities, business development, first-of-a-kind commercial projects, initial manufacturing lines, safety testing and, throughout, additional research to troubleshoot issues and explore improvements. As a rule-of-thumb, the share of spending on labour is highest in the early stages and the share that is on equipment and capitalised assets rises towards early deployment. As the risk of technical failure diminishes, the amount of capital to reach the next technology readiness level (TRL) rises, and the risk of unproductive sunk costs increases.

Somewhere in the middle of this process is a period known as the "valley of death" in hardware-intensive sectors such as energy. At this point, the technological risks are often still too high for institutional and infrastructure finance to take on the projects, and the capital costs are too high for VC funds or R&D grants. The lack of private finance for large-scale demonstrations and first-of-a-kind commercial projects is sometimes called the "missing middle". Some of the largest individual government programmes for energy R&D are designed to plug this particular finance gap. Recent data revisions in this area, especially for the European Union's Innovation Fund and nuclear fusion programme, have changed the overall public energy R&D spending trend compared with last year's report.

Other financial instruments are used by governments to either directly finance projects entering the valley of death or to help them attract more affordable private capital. These instruments include loans (including export credit), equity, loan guarantees, performance guarantees, tax incentives and offtake commitments (see Chapter 4). These sources of government funds add up to billions of dollars each year but are not included in the public R&D data presented in this chapter.

The technology allocation of public energy R&D spending by IEA Member countries has evolved. In 2024, energy efficiency received more funding than other individual technology areas, at almost 30%. More spending is now directed to electricity grids than in any previous period, reflecting the increasing technical need to strengthen grids and make them more resilient (see Chapter 6). The share of nuclear has declined steadily since the 1970s, from 60% to 20%, but this decline has stabilised. Countries have differing R&D priorities and direct their energy R&D spending to technology areas accordingly – the top spending areas of IEA Member countries are provided in the Annex.

Public energy R&D budget per decade with technology shares for IEA Member countries, 1975-2024



Notes: Other power and storage category includes non-transport energy storage applications and energy efficiency includes vehicle batteries and storage technologies. Categories according to the 2011 (not 2025) IEA classification. For definitions of the technology categories, see the IEA Guide to Reporting Energy RD&D Budgets/Expenditures Statistics.

Public R&D data changes since The State of Energy Innovation 2025

Our estimate of public energy R&D spending has changed since The State of Energy Innovation 2025 and World Energy Investment 2025. The primary reason is a revision to data received from the European Commission in relation to spending from the EU budget. There are three notable changes, all of which improve the quality of the estimate and raise the total. Together, the 2023 EU total has increased from the equivalent of USD 2.9 billion to USD 9.2 billion.

- The EU contribution to the ITER-related fusion energy project is now fully included.
- Inclusion of the EU contribution to the projects under the Clean Hydrogen Partnership, a Joint Undertaking for hydrogen research between the European Commission and partners in the research and industrial communities. This Partnership has a variable EU contribution equivalent to around USD 50 million to USD 230 million per year. The high point occurred in 2023.
- Retrospective allocation of awards made under the EU Innovation Fund to prior years, but not included in prior submissions as the final budget appropriations had not been approved. These include awards made under the EU Innovation Fund to energy technology manufacturing projects for early commercial products, as well as performance-based payments to be made against future hydrogen production via the European Hydrogen Bank. While these are both forms of public R&D spending, including demonstration, they differ from the

model of grant-based funding for technology experimentation and development represented by most other entries in the dataset.

Update to the IEA classification of energy technologies

In October 2025, the IEA published a revised classification of energy technologies. This represents the end of a multi-year process of consultation among IEA Members and other stakeholders to bring the prior categorisation up to date. Compared with the previous classification, several important energy technology areas have been either added or reassigned within the system. Innovation and policy have combined to reshape expectations for the energy technology landscape since the last update exercise 15 years ago. From 2026, the new classification will be adopted for sharing of R&D budgets among participating governments.

The changes are not dramatic. A new category has been added for technologies for critical minerals extraction and refining. Carbon capture and storage (CCS) technologies have been separated from fossil fuels, of which they were previously a subset, and carbon dioxide removal has been added. The energy efficiency category has been slightly expanded to include some electrification technologies in end-use sectors. In several other places, including hydrogen and storage, the boundaries between classes have been clarified.

Corporate R&D

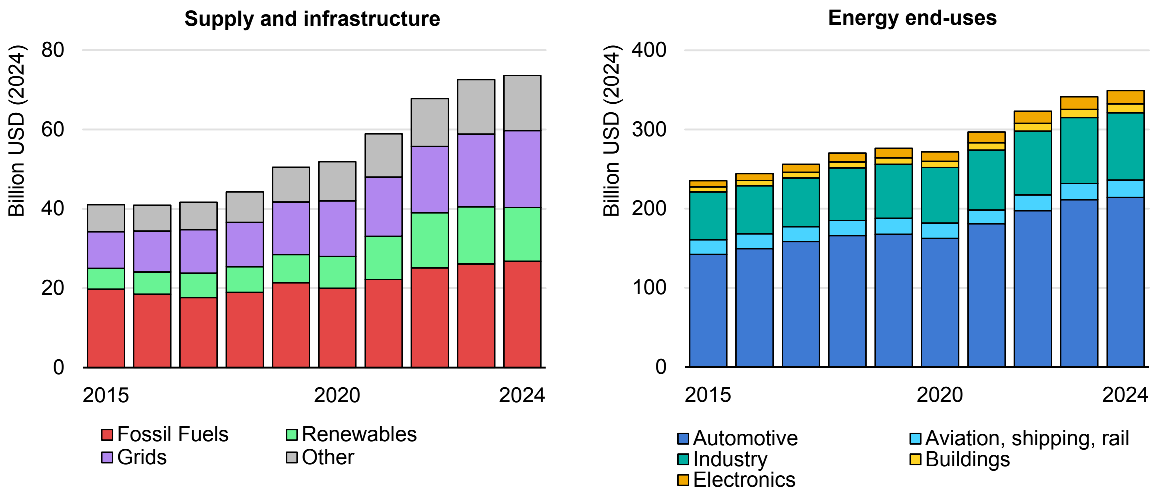
R&D expenditure by corporations operating in energy-related sectors continued to grow in 2024. However, growth was slower than in any year since 2015, with the exception of 2020, when the Covid-19 pandemic prevented many R&D departments from operating normally.

Our tracking of corporate energy R&D counts over USD 160 billion spent in 2024, just 1% higher than the previous year. This count is based on companies' annual financial reports, which are published between March and June with information on the full prior year. Around half of this spending is contributed by companies with reported revenues in energy supply and infrastructure sectors. In 2024, energy R&D in these sectors grew only slightly, as spending in electricity grid and fossil fuel areas compensated for the first decline in the renewables sector since our tracking began in 2015.

The other half of the total is contributed by companies active in energy end-use sectors, for which energy R&D typically represents a much lower share of total R&D efforts. Among these sectors, energy R&D by the automotive sector dominates, with an estimated USD 85 billion spent on vehicle efficiency and electrification. After averaging 9% annual growth between 2020 and 2023, this sector's R&D rose by less than 2% in 2024. As the share of automotive revenues devoted to R&D rose slightly in 2024, the slowdown in absolute R&D spending is most likely linked to lower revenues in the sector and uncertainty about trade policy – an indication of how intense competition and market disruptions can have negative consequences for long-term innovation and, potentially, competitiveness.

Energy R&D spending in non-automotive energy end-use sectors is harder to track because publicly available data are not broken down. However, the total corporate R&D spending that can be attributed to the automotive, aviation shipping, rail, heavy industry, industrial electronics and buildings sectors rose to USD 350 billion in 2024. Most of this is for product development, but energy efficiency and electrification play significant roles in the R&D efforts of these companies, which are mostly on the rise.

R&D spending by listed companies in energy-relevant sectors of activity, 2015-2024



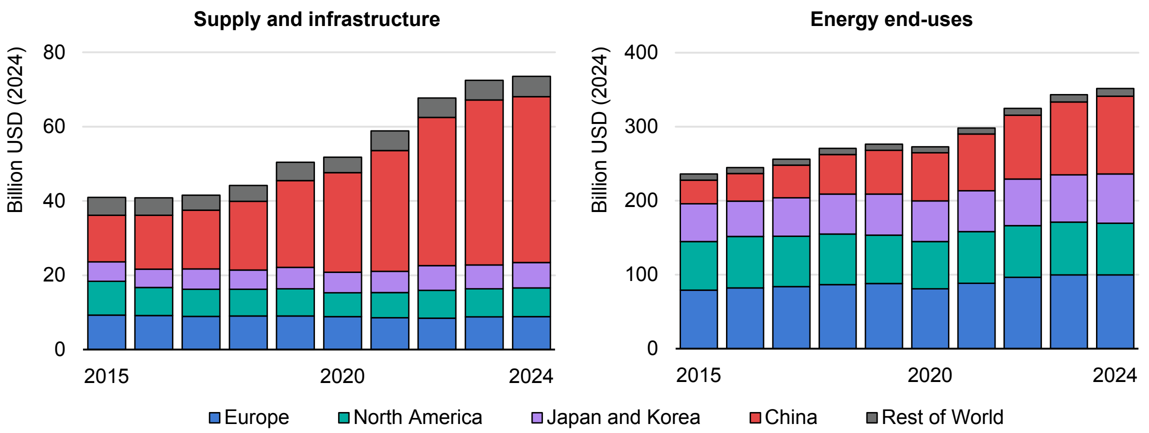
Notes: Due to data limitations, the right-hand chart shows total R&D in these sectors, which is broader than energy R&D. "Other" includes nuclear, hydrogen and power generation not included elsewhere. Includes only publicly reported R&D expenditure by companies active in sectors that are dependent on energy technologies, including energy efficiency technologies where possible, and based on the Bloomberg Industry Classification System. To allocate R&D spending by companies active in multiple sectors, shares of revenue per sector are used in the absence of other information, and the scope is broader than the energy sector for end uses. Values may include both capitalised and non-capitalised costs, including for product development.

Source: IEA analysis based on data from Bloomberg (2025).

This weakening of corporate energy R&D spending in 2024 cannot be ascribed to a single country – there was an absolute drop in corporate energy R&D growth among companies headquartered in Europe, the United States and China. The largest drop was in China, where energy companies raised their level by just 3%, compared with a 15% average over the previous 10 years. Slower growth of corporate R&D spending may be linked to the higher costs of capital faced by firms in 2023 and 2024. It is possible that this led to constraints in overall budgets and that they rebalanced spending away from riskier and longer-term research investments as a result.

Chinese companies represent a greater share of global corporate R&D in energy supply and infrastructure sectors than in energy end-use sectors. These companies have been responsible for most of the growth since 2016. They accounted for 60% of the total for the energy supply and infrastructure sectors in 2024, after trebling their combined spending over a 10-year period. Outside China, total corporate R&D in these energy sectors has remained relatively flat, as rising spending on grids and renewables has been offset by lower spending for oil and gas. Among energy end-user companies, growth in spending by Chinese companies is also stark: together, Chinese automotive and heavy industry companies now spend four times more than they did in 2014. However, overall, Chinese companies occupy a lower share of the global total in these sectors as spending by companies based in Europe, the United States, Japan and Korea accounted for more than 80% of corporate R&D budgets in the automotive sector during the last decade.

R&D spending by listed companies in energy-relevant sectors of activity, by major economies, 2015-2024



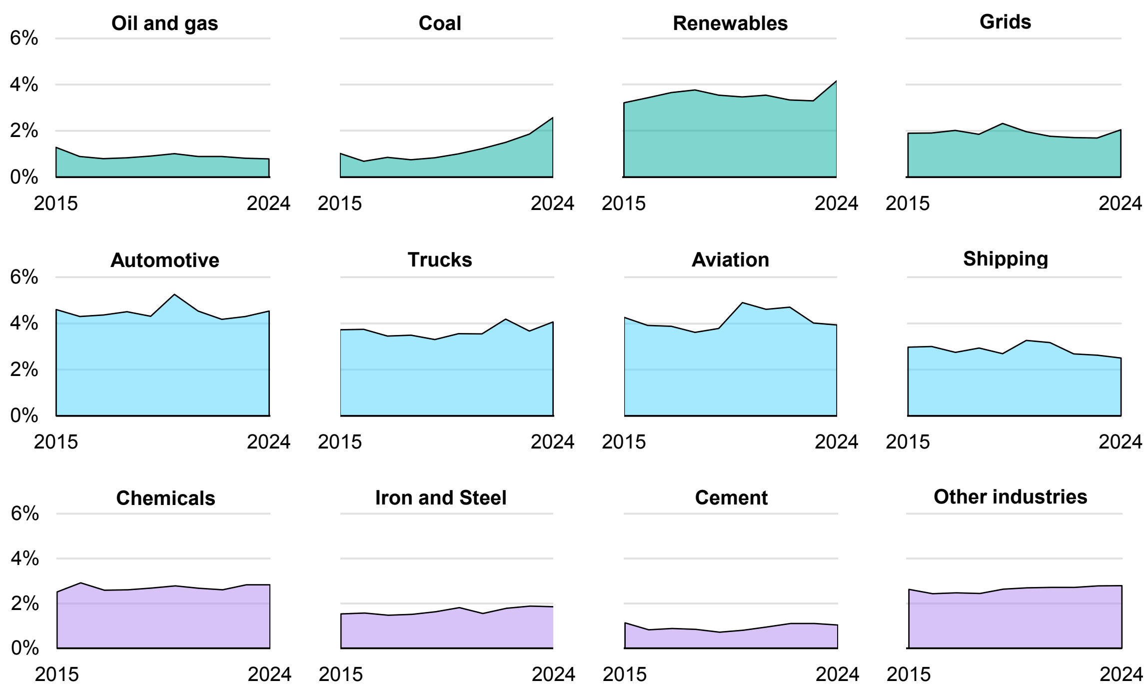
Notes: Based on locations of company headquarters. Due to data limitations, the left-hand chart shows total R&D in these sectors, which is broader than energy R&D. Includes only publicly reported R&D expenditure by companies active in sectors that are dependent on energy technologies, including energy efficiency technologies where possible, and based on the Bloomberg Industry Classification System. To allocate R&D spending by companies active in multiple sectors, shares of revenue per sector are used in the absence of other information, and the scope is broader than the energy sector for end uses. Values may include both capitalised and non-capitalised costs, including for product development.

Source: IEA analysis based on data from Bloomberg (2025).

Trends in corporate R&D spending are typically related to changes in revenue. Many firms spend a strikingly stable share of their revenues on R&D over time, and these levels tend to be similar among companies in the same sector. This implies that budgets are at least in part determined by strategic decisions about the appropriate amount of income to direct to research, devote to capital projects or return to shareholders, in addition to being influenced by emerging technical opportunities. Policy and regulatory incentives can also help improve corporate R&D by companies. Within a sector, the observed levels mirror the importance of ongoing technological innovation to competitive advantage in each sector. For example, this "R&D ratio" is much lower for the oil and gas sector – often a customer of technology as much as an innovator of it – than for renewable energy.

In the coal sector, Chinese companies have recently increased the share of revenue they devote to R&D, possibly reflecting greater focus on environmental protection as well as new markets for coal conversion. Among energy end-users, spending on R&D has increased in several corporate sectors that have been under pressure to develop emerging low-emissions technologies. Iron and steel sector firms have increased their R&D spending from around 1.5% in 2015-2020, to nearly 2% in 2024, and cement companies are now spending more than 1% of their revenue on R&D. Significant trends in transport sectors are less discernible, with the exception of a bump around 2020 that may have been caused by a sudden drop in revenue during the pandemic, combined with a degree of inertia in R&D budgets that are mostly allocated to researcher wages.

Average share of revenue spent on R&D for selected sectors, 2015-2025



Note: Unweighted averages across the largest companies that account for 90% of each sector's revenues globally – between 10 and 200 companies, depending on the sector.
Source: IEA analysis based on data from Bloomberg (2025).

Corporate R&D spending for supply and infrastructure remains highly concentrated within a limited number of companies in most sectors. In the coal, oil and gas, hydrogen, nuclear and grid sectors, fewer than 20 companies represent three-quarters of the R&D spending. In the renewables sector, efforts are slightly more diversified, with 50 companies sharing 80% of R&D spending. Among IEA Member countries, Schneider Electric is the company spending the most on R&D, dedicating USD 2 billion to R&D in the grid sector in 2024, twice as much as in 2015. It represents more than 10% of global corporate R&D spending in the grid sector.

Major corporate R&D spenders in energy supply and infrastructure sectors, 2022-2024

Company	Country	Average annual R&D spending, 2022-2024 (million USD)
Fossil fuels		
PetroChina	China	2 900
Sinopec	China	1 700
Saudi Aramco	Saudi Arabia	1 300
Renewables		
Solar: Jinko Solar	China	780
Wind: Vestas Wind Systems	Denmark	560
Hydro: China Three Gorges	China	200
Grids		
State Grid Corporation	China	2 800
Schneider Electric	France	2 200
Eaton	United States	760
Other		
Nuclear: China National Nuclear Corp.	China	1 200
Nuclear: EDF	France	700
Hydrogen: Bloom Energy	United States	150

In energy end-use sectors, the ten biggest energy R&D spenders are all in the automotive sector, where budgets are significantly higher than those of the top companies in other sectors. However, much of these companies' R&D spending is not dedicated to energy-related challenges such as fuel-efficient engines, aerodynamics and electrification, but also covers safety, driver comfort and digitalisation, including automation. Our estimate of the share directed to energy R&D makes Volkswagen the largest energy R&D spender overall.

Major corporate R&D spenders in energy end-use sectors, 2022-2024

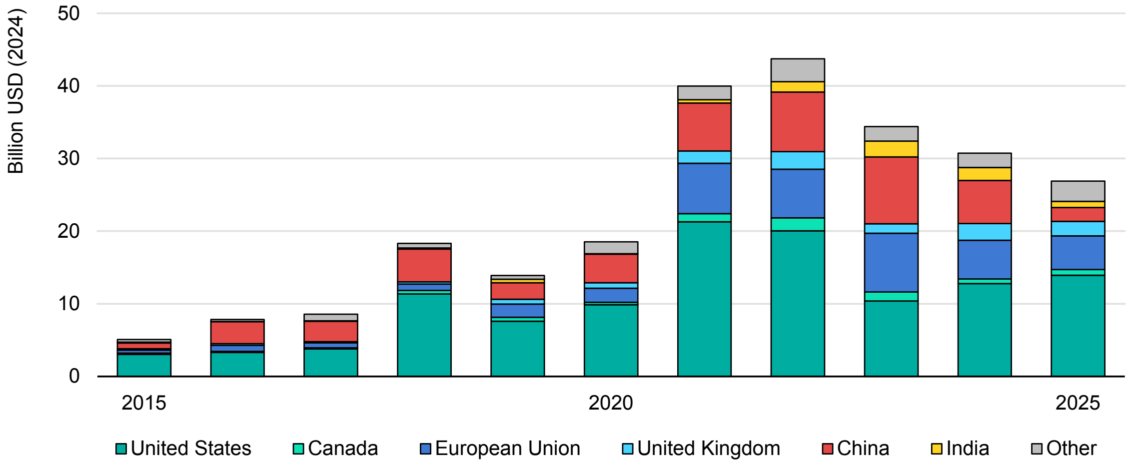
Company	Country	Average annual R&D spending 2022-2024 (million USD)
Automotive		
Volkswagen AG	Germany	23 000
Mercedes-Benz	Germany	11 000
General Motors	United States	10 000
Heavy and long-distance transport		
Airbus	France	3 500
Boeing	United States	3 300
Safran	France	1 600
Energy use in buildings		
Daikin	Japan	750
Saint-Gobain	France	600
Carrier Global	United States	550
Heavy Industry		
Chemicals: Bayer	Germany	7 000
Iron and Steel: Baoshan	China	2 000
Cement: Tianshan Material	China	400

Note: Quoted values are firms' total R&D spending and not an estimate of R&D dedicated to energy challenges.

Venture capital investments

In 2025, total VC funding for energy-related start-ups fell for the third year in a row. A decline of 10% to USD 27 billion puts activity at its lowest level since 2020. In this section, we explore some of the factors behind this trend, and emerging bright spots that are visible in the data. One major contributing factor is that most VC capital is deployed in search of high returns rather than being strategically committed to a particular type of product or impact. As such, at a time when interest rates were low, and other types of investments were not performing especially well, enthusiasm about policies in support of energy transitions helped money to flow to VC in general, and to energy technologies in particular from 2018. When interest rates rose in 2023 and reduced the attractiveness of VC compared to other investments, total VC fell again. When expectations of outsize returns from AI start-ups grew rapidly, a larger share of available VC capital went towards AI.

Venture capital investment in energy start-ups by region, 2015-2025



Note: Incudes early-stage and growth-stage funding.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

Venture Capital data changes since The State of Energy Innovation 2025

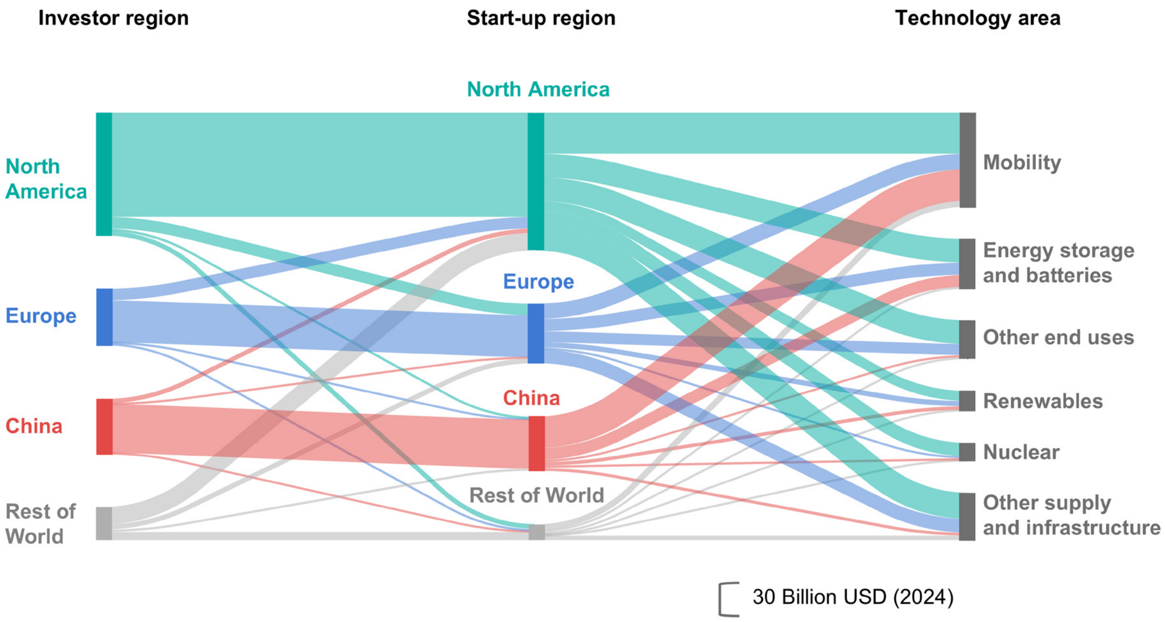
The data presented in The State of Energy Innovation 2026 differ slightly from those in the previous edition. The reflects two main improvements to the dataset used by the IEA:

- The primary data source – compiled by The Cleantech Group – has been further complemented by additional data from Crunchbase. Crunchbase contains details of deals across all start-up sectors. Additional deals for start-ups previously in the dataset have been added, along with additional start-ups not previously in the dataset. Both datasets are processed to fit the IEA classification.
- To keep the analysis focused on energy technology innovation, start-ups have been excluded that are not seeking to commercialise their own intellectual property but are raising funds to deploy third-party technologies (unless otherwise specified). This was not the case in previous IEA analyses, which included a non-comprehensive set of such start-ups.

These two changes, which each represent several billion over recent years, offset one another in terms of total investment.

The United States remains the primary source and destination for energy VC. In 2025, more than 50% of energy-related VC funding was raised by US-based start-ups. The largest single deal in 2025 was for USD 1 billion and raised by Base Power, a US start-up founded in 2023. However, Europe has been closing the gap to the United States and, together, Europe-based start-ups raised the next highest share of VC, at 25%. The largest deal involving a European start-up was for France-based Neot, at almost USD 400 million. China's annual share is highly dependent on the number of very large individual deals, and has been as high as 27% in recent years. However, in 2025 China accounted for less than 10%, the lowest point since 2014. Most funds are invested in start-ups from the same regions – for example, Chinese start-ups are almost exclusively funded by Chinese funds – but there are some cross-border flows. Much of the funding for energy start-ups in emerging market and developing economies comes from Europe, the United States and advanced economies in the Asia Pacific region.

Flows of energy innovation venture capital investments, from investor region to start-up region to technology area, 2015-2025



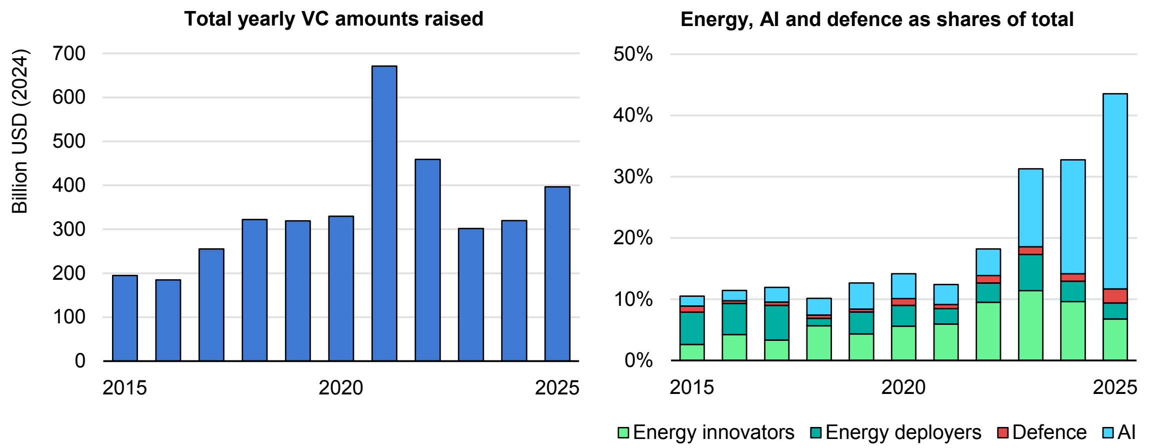
Notes: Deals without localised investors (15-20% of the funding amounts) are distributed among the different regions according to the existing distribution for the start-up's region.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

In recent years, start-ups working on batteries, vehicles or charging technologies for electric mobility have represented a large share of energy VC fundraising. However, VC for these areas is now waning as the sector matures and becomes less reliant on VC, while other technologies are starting to rise. Most VC funding for US energy start-ups in 2025 was for nuclear fission (especially for small modular reactors) and fusion energy. In China and India, VC funding remains highly concentrated in road transport technologies. In Europe, funding in 2025 was more diversified, with hydrogen and energy efficiency occupying a larger share, and electricity grid start-ups also raising a significant share of the total funds. Some technology areas exhibit more geographic concentration than others: start-ups working on geothermal, nuclear fission and fusion energy are much more likely to be in the United States, while mobility, energy networks and storage and heat pumps are more evenly spread globally in terms of both start-up location and source of funds.

Energy VC compared with other sectors, including AI

In 2025, AI deals have dominated total VC funding, representing one-third of all deal value. At almost 7%, energy start-ups developing innovative technologies (including hardware and digital products) raised a lower share of the total than the 10% they averaged in the 2022-2024 period. While energy-related VC dipped further in 2025, the large increase in AI deal value is responsible for a change in the fortunes of the VC sector in general, which returned to growth in 2024, after peaking in 2021 and losing more than half of its value in the 2 years that followed. While much smaller in magnitude, a rise in VC for defence start-ups has also contributed to this rebound. Total VC funding across all sectors was 30% higher in 2025 than 2023. As energy VC was slower than other sectors to decline after 2021 – possibly due to the role of continued policy support in driving energy technology market expectations – the share of energy innovation in total VC peaked later, in 2023.

Total venture capital investment across all sectors, 2015-2025



Notes: AI includes start-ups developing foundational models and AI-specific hardware, infrastructure and security systems. It does not include start-ups applying AI models in other sectors. The Energy deployers category includes energy start-ups that do not develop new technology but deploy certain established technologies.

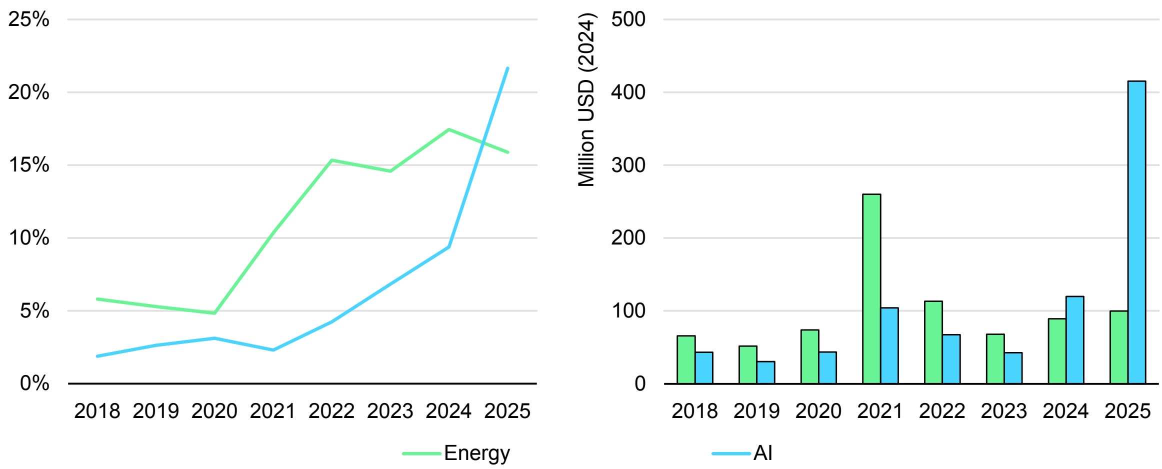
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

The sharp rise in VC investment for AI shows how quickly this type of investment responds to changing market conditions and sentiment. For governments, this is an important reminder that total available public and private innovation funding can vary widely over time unless strategies are in place to smooth such effects.

Such strategies may include making short-term funds available to high-potential innovators that can no longer attract private investors, or using fiscal measures to help guide private funds to priority innovation areas.

There is also some evidence that the largest VC investors previously investing in energy have shifted funds towards AI. Across the 50 largest funds that have invested in energy start-ups, specialisation in funding energy innovation has slowed down since 2022, corresponding with the rise of investments in AI. Of them, 90% have financed at least one AI start-up and their average investments in AI amount to USD 400 million in 2025.

Shares of energy and AI among the investments of large venture capital funds that invest in energy (left), and their average invested amounts by sector (right), 2018-2025



Notes: Data shown are averages for the investors in the studied cohort. The large venture capital funds in the cohort include the 50 that have invested more than USD 1 billion across all sectors and USD 100 million in energy innovation since 2020. Energy includes only technology innovation start-ups. Energy deployment start-ups are excluded.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

Smaller funds that invest less than USD 100 million per year on average in start-ups, are less likely to have shifted from energy to AI, or shifted only in 2025. This may reflect the higher likelihood of smaller funds having strategic mandates to focus on narrower sectoral portfolios. However, large investors can drive overall energy-related outcomes: the 50 largest funds represent 20% to 30% of energy innovation VC between 2020 and 2025.

Unpacking the decline of energy VC, by funding stage and technology

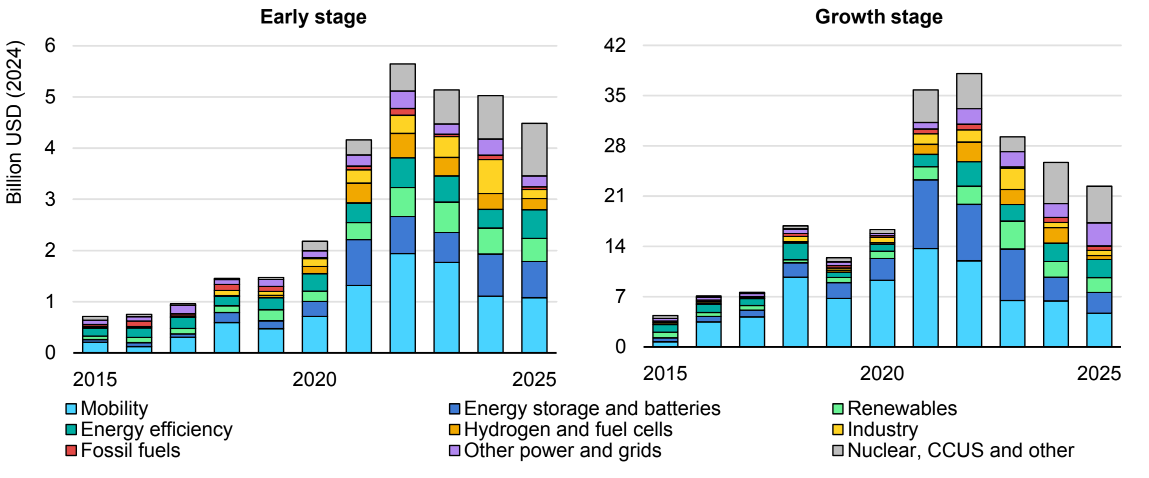
There is no single reason for the decline in energy VC funding since 2022. A range of drivers are in play besides the recent shift of some investors towards AI. Six such considerations are explored in this section. These include a risk environment

– with higher interest rates and an uncertain macroeconomic outlook – that encourages all types of investors to make fewer investments and to wait longer before investing. The diversity of technology trends also plays a role, with a possible transition from an investment cycle for electric mobility to new cycles for a set of emerging technologies. These considerations can all provide relevant insights for how governments can help ensure innovators have access to capital.

Early-stage funding remains stable

The ability of young energy start-ups to raise early-stage funding has remained relatively stable since 2022, declining by just 20% and remaining significantly higher than the 2021 total, while growth-stage funding decreased by 40%. This indicates that investor interest in funding the testing and prototyping of high-potential ideas has not diminished, despite higher interest rates. In this regard, energy remains a high-performing part of the overall VC landscape. However, early-stage deals are relatively small – often less than USD 10 million – and not sufficient to bring a technology to commercialisation. Without growth-stage funding, many start-ups that could become competitive will face insolvency or a forced acquisition before being able to reach the market.

Venture capital investment in energy start-ups, by technology area, for early-stage and growth-stage deals, 2015-2025



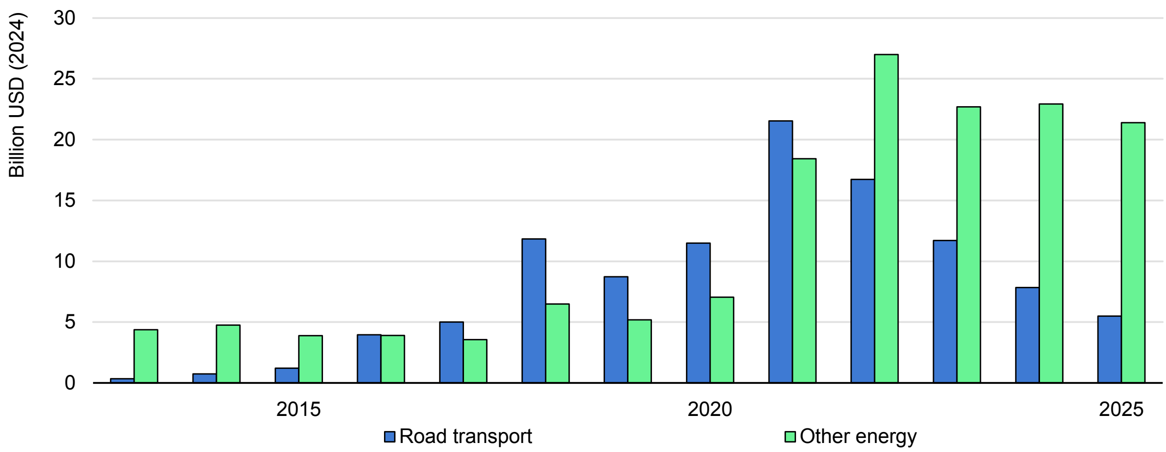
Notes: See the Annex for the classification of early- and growth-stage funding. “Industry” includes start-ups developing alternative pathways to materials. “Mobility” includes technologies specific to alternative powertrains, their infrastructure and vehicles, but not generic shared mobility, logistics or autonomous vehicles. CCUS = carbon capture, utilisation and storage (CCUS). “Other” includes carbon dioxide removal (CDR), critical minerals and heat generation. Fossil fuels cover start-ups which aim to make fossil fuel production and use more efficient or less polluting.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

The end of an electric vehicle funding cycle has led the decline

Energy VC trends are also influenced by cycles of interest in different energy technology areas. Compared with public and corporate R&D spending, VC is much more responsive to changes in market and policy outlooks, as well being susceptible to hype. The most pronounced of these cycles in recent years has been the rise and fall of funding for start-ups working on EVs and their batteries. The rapid influx of funding in 2017-2021, one-third of which was raised by Chinese start-ups, coincided with a step-change in the deployment of electric cars worldwide. A total of 450 electric car models were available on the market by 2021 – five times more than 2015 – and sales rose from around 0.5 million per year to over 6 million per year over the same period. The creation of an established electric car industry in this period drove standardisation and consolidation. However, five new EV makers have gone out of business since 2022, after raising over USD 6.5 billion between them. The valuations of five other listed companies that have raised close to USD 50 billion between them fell significantly. After 2021, VC investors allocated much less capital to a technology area that became harder to break into: VC investment fell from USD 22 billion to USD 5 billion over 4 years.

Looking only at energy VC funding to start-ups outside the area of EVs and their batteries, the overall trend has been closer to a plateau since 2021. This implies higher resilience of energy VC in non-EV areas than is commonly understood and highlights the importance of cyclical trends within technology fields.

Energy venture capital in road transport and other energy technology fields, 2015-2025



IEA. CC BY 4.0.

Note: Road transport category includes electric vehicle battery developers and makers.
Source: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

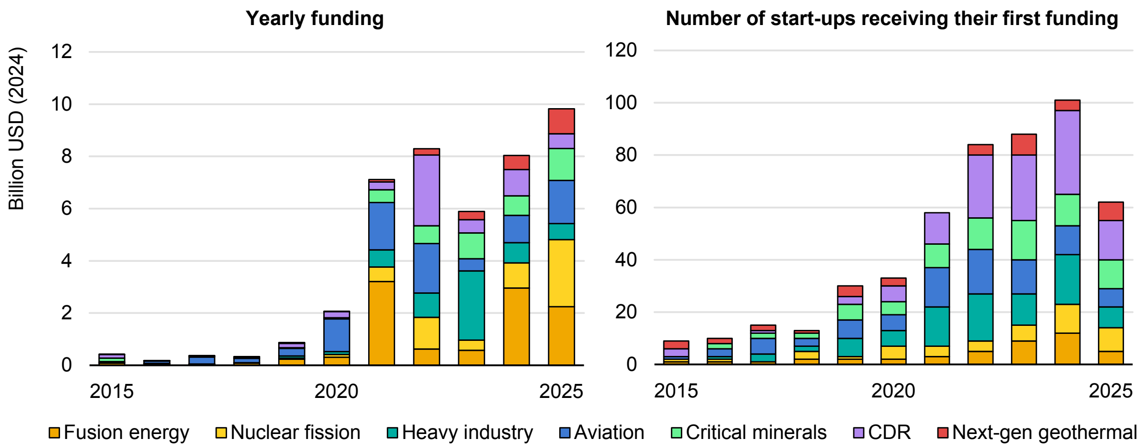
Another earlier VC cycle was for solar PV, for which related technology development represented almost 25% of energy VC between 2006 and 2010, but has been less than 5% of the total since 2016 (deployment start-ups in solar PV have raised more than this but are outside the scope). Hydrogen technologies have also followed cycles in recent years, though more muted than for solar PV: from 2009 to 2014, hydrogen-related funding accounted for 5% of energy VC funding, then, after falling to 1%, rose again to 7% between 2020 and 2024. It stood at 3% in 2025.

New emerging areas are offsetting the decline in funding for electric vehicles

If energy-related VC is influenced by cycles of enthusiasm for individual technology areas – and early-stage VC has been resilient – then a closer look at the data may reveal the next growth technology.

Seven technology areas – carbon dioxide removal, critical minerals, geothermal, low-emissions industrial production, aviation, nuclear fission and nuclear fusion – have been responsible for offsetting part of the decline in electric vehicle VC funding since 2021. In 2015-2020, these seven areas represented less than 5% of total energy VC funding (of which aviation accounted for half). In 2025, they represented more than one-third of the total funding. As a sign that these areas are on a growth trajectory, the number of new start-ups founded to work on these technologies is rising steeply. In the past 10 years, 400 start-ups have been founded and received funding in these technology areas. Over 60% of these were founded after 2020 and the average age of start-ups receiving their first funding in 2024 and 2025 in these areas was slightly above 3 years. In 2025, even though funding amounts increased, just USD 1 billion went to energy start-ups raising their first funding, compared with USD 2 billion in 2024.

Equity funding of start-ups in seven emerging energy technology areas, 2015-2025



Notes: CDR = carbon dioxide removal. Next-gen geothermal = Next-generation geothermal. Heavy industry excludes chemicals, an area that was raised significant funding before 2020.
Source: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

An interesting feature of this portfolio of emerging technologies is that it includes several that have traditionally been considered a poor fit with VC funding. Three of the six largest deals of 2025 were for nuclear technologies that require large-scale projects with long development cycles and capital costs in the hundreds of millions or billions of dollars, and others among the six emerging areas have similar profiles. Until recently, the rise of energy-related VC funding was closely linked to the arrival in the energy technology landscape of more mass-manufactured technologies, such as batteries, and digital technologies that can scale up relatively quickly from niche to mass markets. For these technology types, finance from energy sector incumbents, whose capabilities were focused on larger-scale and less disruptive equipment, was lacking, and many generalist VC investors found the financial returns in the energy sector to be slower than they needed. In contrast, specialised and corporate investors, including big digital firms, have provided a significant share of the funds raised for the seven emerging technology areas. However, whether this represents a new phase in energy VC investment, with more patient investing by strategic funds, remains unclear.

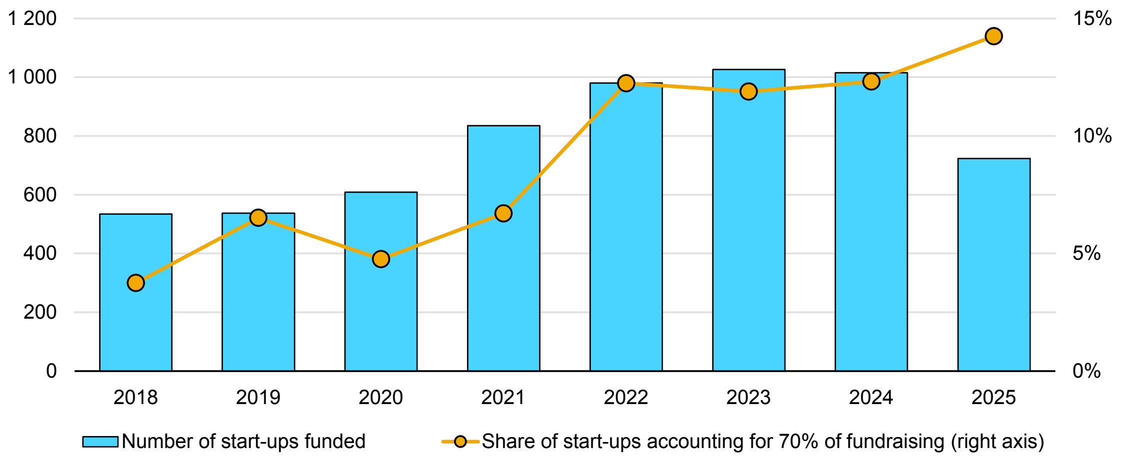
- Deals in **fusion energy** can involve very large sums of money, even though the related technology is still at a very early stage. In 2025, the largest deals were concentrated in the United States: Commonwealth Fusion Systems, raised USD 860 million with the aim of building and operating a magnetic confinement demonstration project by the early 2030s, and Helion Energy raised more than USD 400 million towards a magneto-inertial confinement demonstration project they aim to operate by 2028. Outside the United States, the largest deal was for a German start-up, Proxima fusion, which raised USD 140 million .
- The growing VC investments in **nuclear fission** are mainly driven by the development of small modular reactors (SMRs). In 2025, Terra Power, a US start-up, raised USD 633 million to develop a sodium-cooled SMR, and X-energy, also a US start-up, raised USD 700 million to develop a high-temperature, gas-cooled SMR. Only US start-ups raised more than USD 100 million.
- Funding for **critical minerals** reached a record high in 2025. Kobold metals, a US start-up, raised USD 535 million, and GeologicalAI, from Canada, raised USD 44 million. Both combine geological data, satellite imagery and AI to speed up exploration. Cornish Lithium, a UK firm, raised USD 45 million to further develop its lithium extraction technique, while Genomines, a French start-up, raised USD 45 million for phytomining technology, a means of using plants to extract minerals from the soil.
- Funding for **next-generation geothermal** also hit a new high in 2025, with 11 firms raising nearly USD 1 billion combined, half of which was raised by just one US start-up, Fervo Energy.
- Relevant deals in **heavy industry** in 2025 mostly concerned start-ups working on cement and iron and steel. Electra Earth and Terra CO_2, two US start-ups, raised a combined USD 300 million for steel and cement technologies, respectively.
- Funding in **aviation** was largely for electric aviation. Beta Technologies and Electra Aero, two US start-ups, raised over USD 300 million and USD 100 million respectively. In the area of hydrogen-powered flight, Hypersonix Launch Systems, an Australian firm, raised USD 46 million to develop a hypersonic concept.
- Deals in **carbon dioxide removal** in 2025 included 16 different start-ups developing direct air capture technologies. Climeworks, a Swiss firm, raised

USD 162 million, bringing its total funding to over USD 1 billion. In the United States, [Aircapture](#) raised its first funding of USD 50 million, while [Remora Carbon](#) raised USD 60 million to develop on-board capture for trucks and rail.

Lower funding levels are shared among fewer start-ups

In 2025, the average energy VC deal raised USD 30 million, a new high after steady decline since 2022. However, the number of funded start-ups decreased by more than 30%, from 1 000 per year on average in 2022-2024 to 700. This decline affects both early- and growth-stage. During the boom in energy VC funding in 2019-2022, the additional capital funded more start-ups and provided each one with more equity on average, and therefore longer financial security before having to raise new funds for technology development. In 2022, 60% more start-ups were funded compared to 2020, and 12% of them accounted for 70% of total funding, a record high compared with levels previously at 6%. After 2022, the total number of funded start-ups remained high, but with a decline in funding levels per start-up. This suggests that part of the initial response to a higher cost and higher risk macroeconomic environment has been to place smaller bets across a diversified portofolio. However, in 2025, the trend appears to have come to an end: the number of funded start-ups fell sharply, returning close to pre-2020 levels, and a smaller number of start-ups raised more on average than the year before.

Energy start-ups funded and the share responsible for 70% of funding, 2018-2025



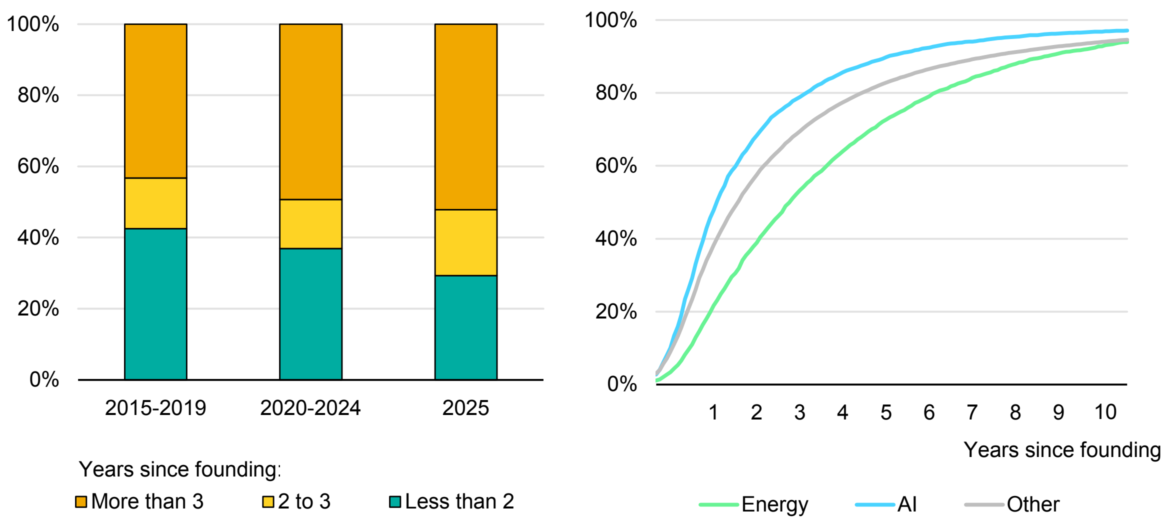
Note: The share represents the smallest number of start-ups in each year whose combined fundraising sums to at least 70% of all energy VC fundraising in that year, divided by the total number of energy start-ups funded in that year.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

There are sectoral and technology differences in deal value and concentration, however. Energy innovators continue to raise more on average per deal than start-ups in other industries, such as biotechnology (USD 26 million in 2025) and financial technology (USD 25 million in 2025). Within energy, some technology areas have funding that is even more concentrated among fewer start-ups. For CCUS, critical minerals, geothermal, aviation, shipping, nuclear fission, fusion energy and industry, fewer than 10 start-ups account for over 50% of fundraising for the 2020-2025 period.

Energy start-ups are waiting longer to raise funds

Energy start-ups, especially those developing hardware products, often face an extended and uncertain path to market. Designing, prototyping and testing technologies requires time, capital, and, sometimes, access to regulated infrastructure and other facilities. In 2025, half of the energy start-ups that raised funds for the first time were more than 3 years old, up from 40% in 2015-2019. On average, as VC funds have been cut back, it is taking longer for energy start-ups to raise capital. This is against a backdrop in which energy start-ups already had a longer route to funding than their counterparts in other sectors. In other sectors, 50% of start-ups on average have raised their first funding round after 1.5 years, while for AI start-ups this is as short as 1 year. However, first deals are generally larger in the energy sector, with the median deal totalling USD 3 million, compared with USD 1 million in other sectors.

Share of energy start-ups raising a first funding round by age (left) and shares of start-ups raising first funding rounds in the years since founding by sector, 2010-2025



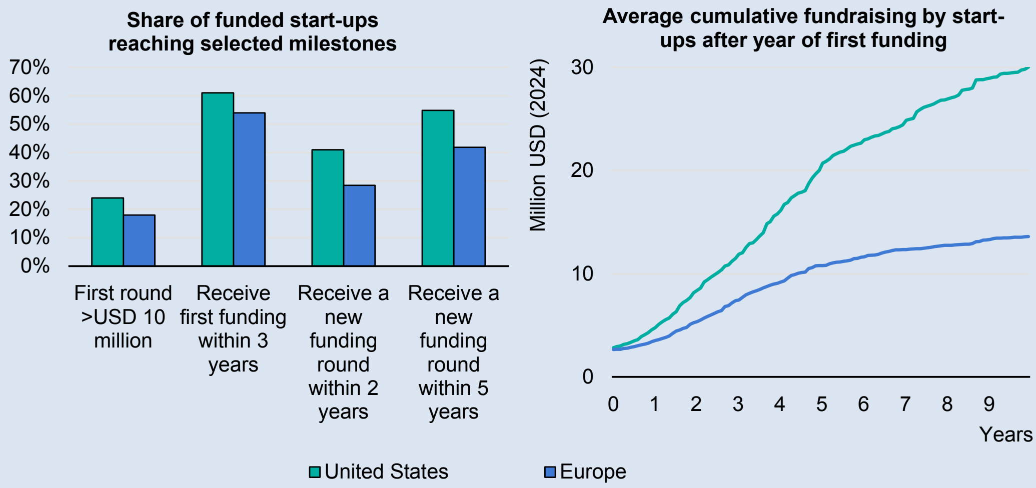
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

US energy start-ups are raising more money, more quickly

In 2025, the difference between European and US energy start-ups widened in terms of fundraising speed. Almost 55% of European energy start-ups raising their first equity in 2025 were more than 3 years old, compared with 45% in the United States. This is a slightly larger gap between the regions than seen on average between 2015 and 2024. In addition, just 25% of European energy start-ups raising their first funding in 2025 raised over USD 10 million, compared with 40% in the United States.* For the United States, this value has grown from around 25% on average between 2015 and 2024. The difference is larger at the second round of funding – a crucial step in the life of an energy start-up because more than half of those that secure a first round never reach a second round within a 10-year period, reflecting the energy sector's capital intensity, long timelines and technical risk hurdles. Between 2010 and 2025, 40% of US energy start-ups raising a first round of equity funding successfully raised a second round within 2 years. Only 30% of European energy start-ups achieved this, and 56% never raised a second round, compared with 44% in the United States. In general, if an energy start-up does not raise a second funding round within 5 years after its first round, its chances of raising further funding are small.

* To some extent, this may be balanced by a higher availability of grants for European start-ups and a lower-cost route to scale-up in Europe for certain technology areas.

Comparison between US and European energy start-ups on different metrics



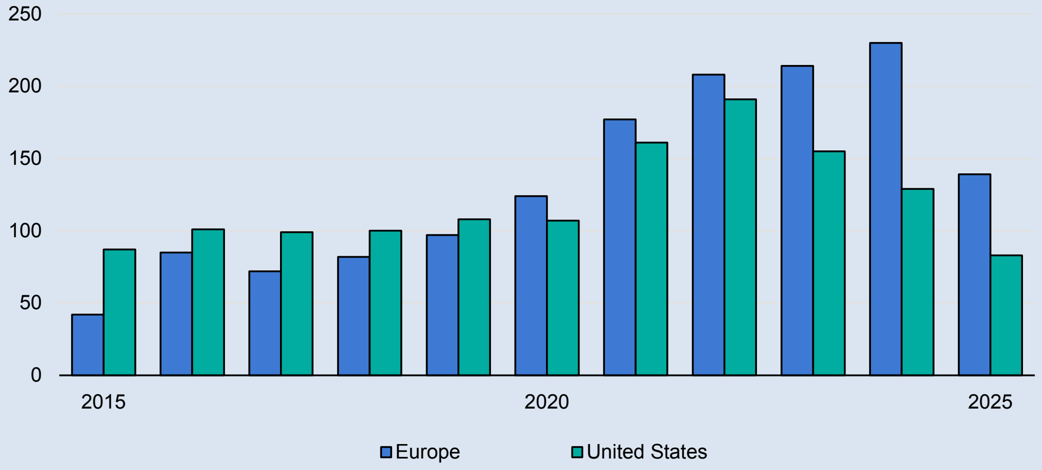
Notes: Average cumulative funding excludes large fundraisers (top 10% by funding) to avoid skewed results. Based on 2010-2025 data.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

With regards to funding amounts, the largest differences are observed for the 90% of energy start-ups whose first rounds are less than USD 20 million. These are typically start-ups at an early stage of technology development when they are founded, or working on less capital-intensive hardware. Between 2010 and 2025, for these start-ups, the average size of the first funding round was the same in the

United States and Europe. But US start-ups in this category had an expected fundraising value that was 50% higher than their European counterparts in the 2 years after this first round, and 100% higher for the 6 years after this first round.

On the other hand, the number of new start-ups raising money is becoming bigger in Europe than the United States. Since 2024, 370 European start-ups have raised a first funding round, more than the equivalent number of US start-ups, at 210. Moreover, this number has been declining since 2022 for the United States and has been lower than the number in Europe since 2019.

Number of energy start-ups raising their first equity per year in the United States and Europe, 2015-2025



Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

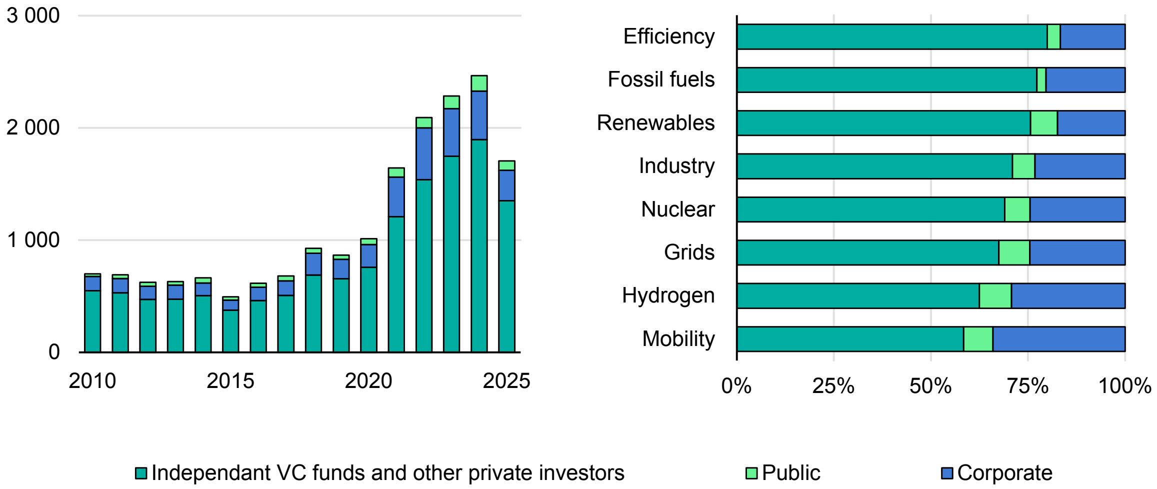
Strategic investors have not stepped up

The reduction of total VC funding for energy start-ups since 2022 raises policy-relevant questions about whether certain investor types have remained more dependable for innovators than others. IEA analysis distinguishes between public sector-managed funds, corporate venture capital (CVC) and others, including most VC funds and financial institutions. The first two of these categories are strategic investors that are motivated by more than the 5-year return on capital invested that motivates other fund types. Public sector funds seek to support start-ups in energy technology areas that have a low likelihood of short-term returns but a higher chance of making a long-term contribution to policy priorities and economic growth. CVC funds seek to widen their parent company's internal knowledge, nurture potential future suppliers of equipment that is not yet available and create opportunities to enhance their operations areas via acquisitions. They are specialised: among the 100 largest CVC investors in energy start-ups, around half invest over 80% of their funds in energy technologies. In return, start-ups often get access to knowledge about customer requirements and access to collaborative trial projects.

The average number of public and corporate strategic investors investing annually in energy in 2021-2025 was double that in 2016-2020. In emerging market and developing economies, public funds represent a higher share, at almost 20% over 2021-2025. However, the estimated share of funding from strategic investors globally remained constant over 2021-2025, at around 30%, and one-quarter of the total number of investors. In 2025, the share of CVC was 20% of funding and for public funds it was 5%. The implication therefore is that strategic investors do not on average provide a more stable source of equity funding for start-ups when non-strategic investors pull back.

Strategic investors have been more important in some energy technology areas than others. Between 2020 and 2025, the share of CVC was highest for mobility technologies, mostly involving firms from the automotive supply chain. This was followed by hydrogen, electricity grids and low-emissions industry technologies. Public funds are most present in deals in the same technology areas, suggesting that these sources of capital reinforce one another, rather than complement each other by targeting different technology types. One possible reason why this may be a positive outcome is that technology areas such as hydrogen, grids and heavy industry are expected to have high development costs and longer pathways to commercialisation. The case for strategic investment to fill funding gaps and attract other forms of private capital may be stronger in such cases.

Number of venture capital investors funding energy start-ups (left) and splits of funding by investor type, by technology area, 2010-2025

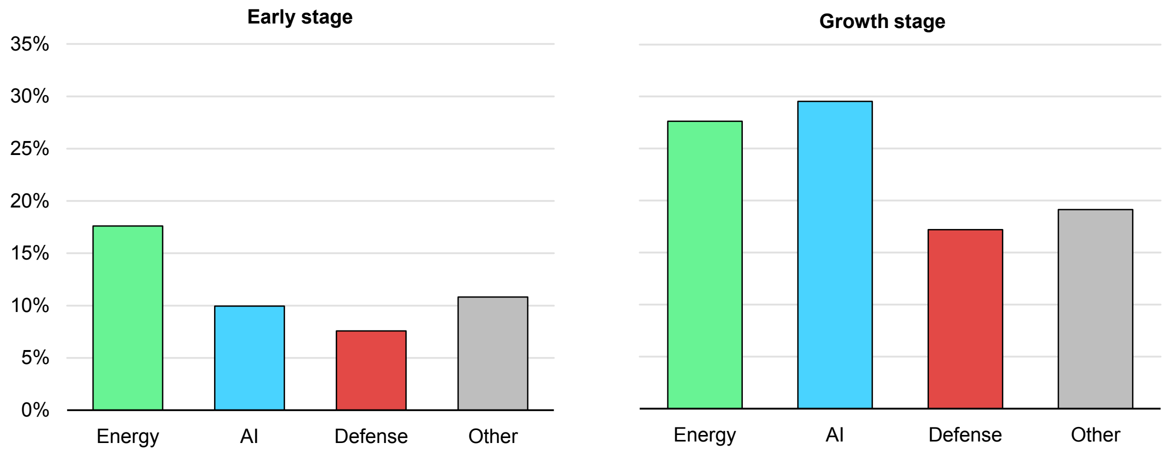


IEA. CC BY 4.0.

Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

Compared with other sectors, energy start-ups are more dependent on CVC for early-stage deals. Their share of 18% of funding for energy start-ups in 2010-2025 is higher than the share of around 10% for non-energy sectors. Given this importance of strategic investors for the development of long lead-time energy technology projects, policy makers could consider how to encourage partnerships between start-ups and corporations, as well as how to improve the incentives for CVC funds to respond with more restraint than other VC funds when macroeconomic conditions change. Energy innovation start-ups are also more dependent on CVCs for scaling up, with these funds representing 25% to 30% of funding in these sectors, compared to 20% elsewhere (excluding AI).

Share of corporate venture capital in total venture capital funding, by sector, 2010-2025



Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

Among other VC funds, there has been a rise of more specialist energy and climate VC funds in Europe and North America. While these funds are primarily driven by returning value to their limited partners (providers of capital to the fund), they sometimes have an objective to ensure social or environmental impact that allows them to be more patient for returns and therefore quasi-strategic. In 2023-2025, 50% of energy investors with more than 5 start-ups in their total portfolio were energy-specialised (more than half of their portfolio was energy). In 2020-2022, it was only 35%.

However, fewer investors in 2025 added multiple energy start-ups to their portfolios. Around one-third fewer investors (excluding CVC and public funds) funded five or more different energy start-ups in 2025 compared with 2024. Nearly 40% fewer investors (excluding CVC and public funds) invested in three or more distinct energy technology areas in 2025 compared with 2024, when there were more such investors than in any previous year. In 2025, Breakthrough Energy Ventures and Lowercarbon Capital, two US VC funds, had the most diversified portfolio of energy start-ups: both invested in 8 different energy areas.

Chapter 3. Patenting

As one of the methods of tracking energy innovation, the global patent landscape provides a unique perspective on where technology development is taking place, which topics are receiving most attention, and where new innovations are being developed most quickly. Although it cannot shed light on which inventions will be successfully developed and impactful in the marketplace, tracking patenting activities can help to quantify outputs of investments and innovation policies at different levels. The IEA collaborates with the European Patent Office (EPO) to track specific patent trends relevant to the energy sector, and specific trends in dynamic technology areas such as solar, hydrogen, grids and storage technologies.

This chapter highlights the latest trends in energy technology patenting, including differences in what patents focus on in major world regions. It also analyses past patenting trends relating to solar PV technologies and batteries used in electric vehicles (EVs) – two areas which have seen rapid advances in recent years – to explore how early deployment relates to innovation. Finally, it examines emerging technology areas that are attracting an increasing share of patenting activity.

Trends in energy technology patenting

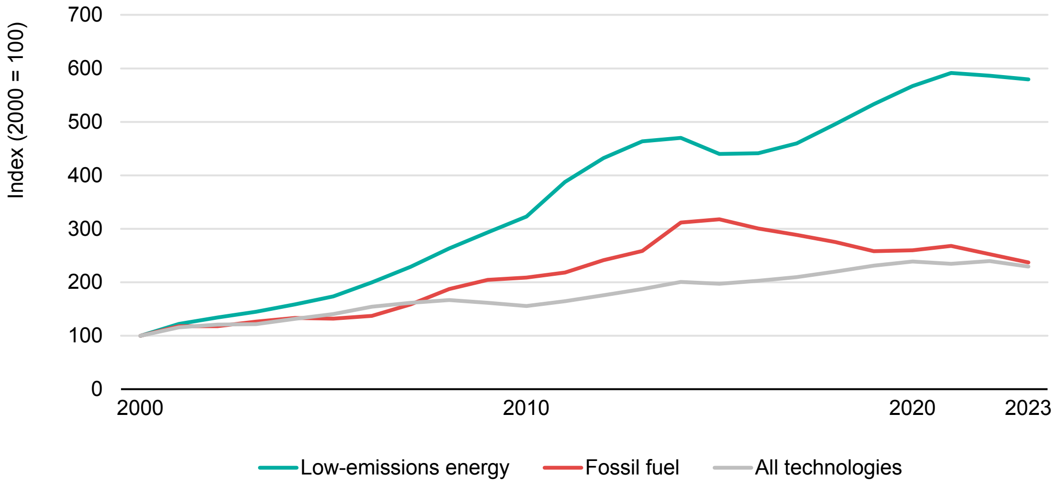
Since the beginning of this century, energy technology patenting has grown to represent around 10% of all technology patents from 2020-2024, ahead of other important sectors such as chemicals, pharmaceuticals and transport. There have been around 180 000 international patent families (IPFs) in energy technologies since 2020.[5] This growth has been driven by a sharp increase in the number of patents from China, which overtook the United States to become the world leader on energy technology patenting in 2021. In addition, the number of patents for low-emissions energy technologies have increased by approximately 79% since 2010, more than offsetting a decline in fossil fuel patents over the same period.

The number of patents for low-emissions energy technologies fell by 1% in 2023, the latest year for which comprehensive data are available. This continues the moderate decline seen in 2022. There are several possible reasons for this. One relates to patenting in general, which declined 4% in 2023 and may relate to the continuing effects of a slowdown in activity during the Covid-19 pandemic. Another

[5] Each IPF represents a unique invention and includes patent applications to two or more counties or jurisdictions including at least one international patent office. As such, they indicate inventions that hold commercial promise in multiple jurisdictions and are a means of controlling for patent quality. IPFs are allocated to the year in which the first patent application for the invention was filed worldwide. In this chapter, patenting refers exclusively to IPFs.

is a decline in patenting in end-use energy technologies that began in several major economies in 2020 but was previously outweighed by growth in energy supply-side technologies. A leading contributor historically to patenting in end-use technologies has been innovation in combustion engines for vehicles, which appears to be in structural decline, with growing expectations that future competitiveness in vehicle value chains will come from innovation in electric drivetrains. Fossil fuel patenting – a category that mostly represents supply-side technologies – continued its gradual decline in 2023, falling by 6% compared to 2022, and extending the downward trend that started in 2016.

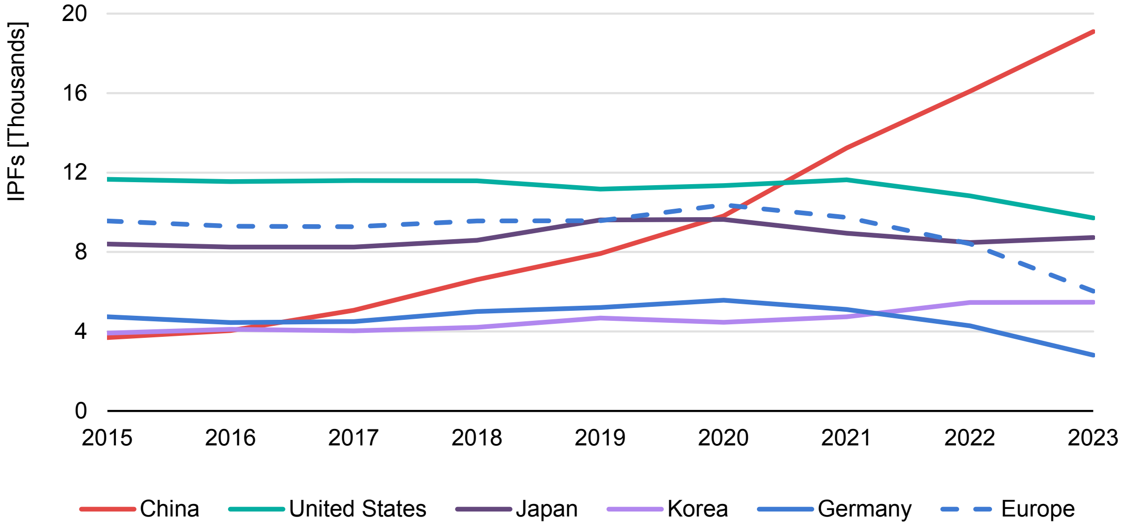
Global evolution of patenting in low-emissions energy, fossil fuel and other technologies, 2000-2023



Notes: Shows a count of international patent families, each of which represents a unique invention and includes patent applications filed in at least two countries. All technologies refer to all technological sectors, including energy.
Sources: IEA analysis based on December 2025 data from the European Patent Office (EPO), and EPO and IEA (2021), Patents and the Energy Transition.

Internationally, the headline story remains the growth in energy patenting in China compared with other major economies. Patent applications from inventors located in China grew approximately 20% in 2023, continuing the growth of recent years. Energy technology patents from China have risen more than five times since 2015, while patenting in other countries responsible for major shares of global IPFs has largely plateaued or even declined in recent years. In 2023, China represented close to two-fifths of all energy patenting. In contrast, energy technology patents from the United States fell by 10% between 2022 and 2023, while Europe recorded a third consecutive annual decline, with energy patenting falling by 28% over the same period.

Energy patenting of the five countries with the most applications, plus Europe, 2015-2023



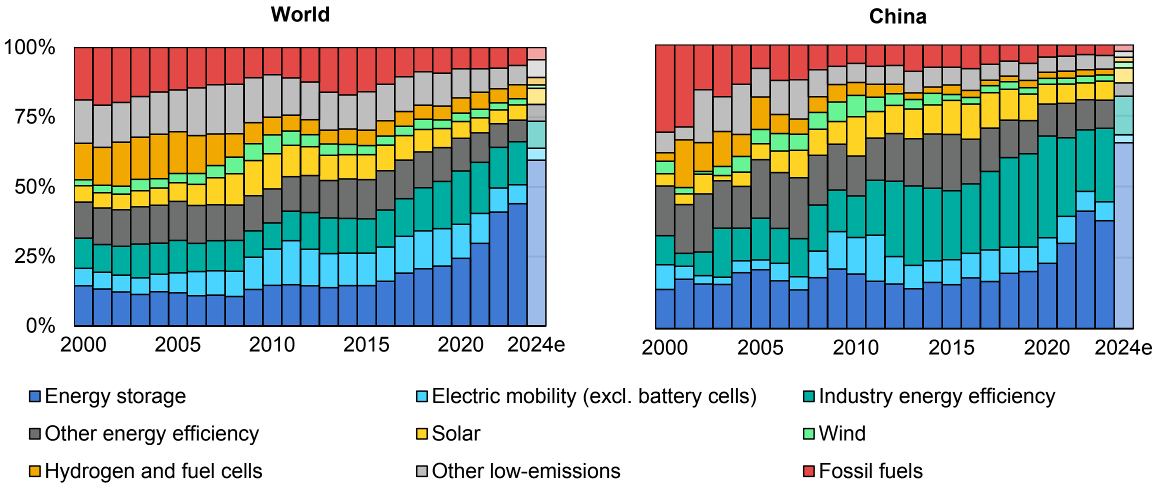
Notes: Shows a count of international patent families (IPF), each of which represents a unique invention and includes patent applications filed in at least two countries. Where multiple countries are associated with the different inventors for the same IPF, fractional counts are applied. Europe represents member countries of the European Patent Convention.

Sources: IEA analysis based on December 2025 data from the European Patent Office (EPO), and EPO and IEA (2021), Patents and the Energy Transition.

Among major patenting countries, patents relating to low-emissions technologies now make up the vast majority of energy technology patents and represented as much as 97% of all IPFs in China in 2023. This share was 80% for the United States, 96% for Korea and Japan, and 68% for Europe, showing little change from the 2022 shares. Between 2020 and 2024, China filed one-third of all patents related to low-emissions energy globally, which represented over 95% of all energy patents filed by China over the period.

Globally, the distribution of technologies within energy patenting has undergone a dramatic shift towards energy storage. Between 2015 and 2023, the share of energy storage in total energy patenting rose steeply from 15% to over 40%, largely relating to new battery technologies. Based on very preliminary data already available for 2024, which so far only cover a small share of the total applications that will eventually enter the dataset, the share of energy storage could rise even further and pass the 50% mark. Other technology areas have seen their shares squeezed, despite maintaining relatively steady absolute numbers in some cases. These include fossil fuel supply technologies, energy efficiency, hydrogen and electric mobility. In 2023, industrial energy efficiency and solar energy were the next largest areas after energy storage, but trailed far behind.

Energy patents by technology in the world and in China, 2000-2024e



Notes: "Other low-emissions" includes aviation, rail, marine, bioenergy, carbon capture and storage, electricity grids, nuclear and renewables (including those integrated into buildings). "Other energy efficiency" includes agriculture, buildings, road transport. Based on international patent families (IPFs), each of which represents a unique invention and includes patent applications filed in at least two countries. 2024e: estimated. It is very preliminary and only includes low share of IPFs that will eventually enter the dataset for that year. Technology categories follow Y02-Y04S scheme for low-emissions technologies (i.e. energy storage includes Y02E 60/10-16 and Y02E 70/30) and IEA and EPO methodology for identifying fossil fuel technologies in patent data.

Sources: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

Patent system reform in China

In 2025, the Chinese government took measures to enhance its intellectual property regime as part of an ongoing process of reform. Among other measures, the standards for patent approvals in emerging technology areas from 2026 were raised, and initial indications of how this might be applied to solar PV were published. Other areas of reform include strengthening the framework for awarding damages to patent holders and making patent examination more transparent. The cumulative impact of these reforms is thought to have already contributed to a decline in patenting in China in 2025 compared with 2024. These changes may therefore influence how China's energy patenting evolves after 2023 in future editions of this report. However, the impact is expected to be modest. By using IPFs rather than only national Chinese patents, we already control for patent quality. In addition, the incentives for innovators to apply for patents in China as early as possible remain, potentially increasing Chinese patent counts in earlier years of our data, as we use the year of first filing.

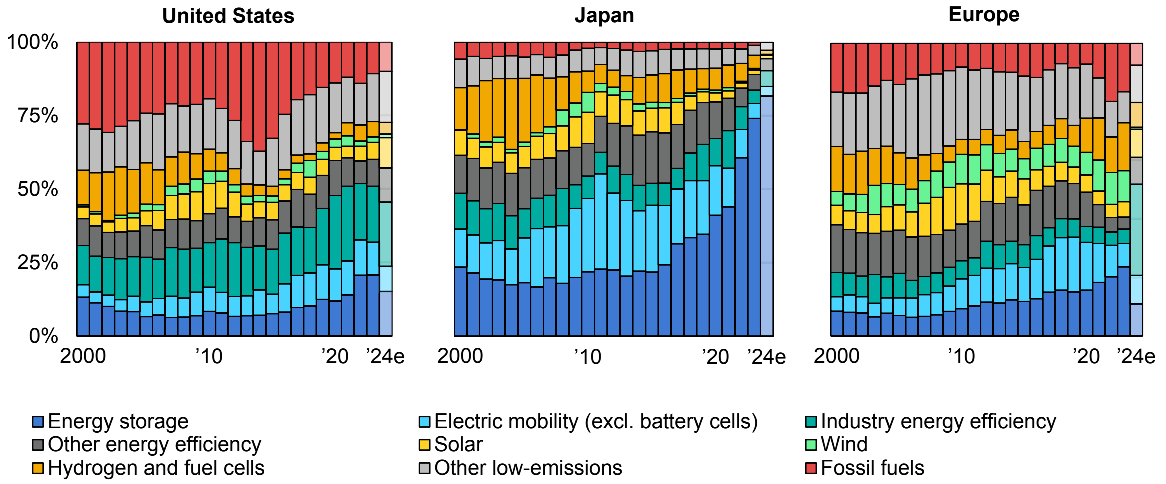
Energy patenting dynamics in China differ from the global trend in several areas. Up until 2023, the rise of energy storage was less pronounced in China, but still reached over one-third of the total. The preliminary 2024 data suggest that this may change in that year, bringing China closer to the global share and in part driving the global trend. If the 2024 trend is borne out by future data updates, it will reflect the importance that China has placed on leading advanced battery manufacturing and EV technology in recent years. Chinese battery companies, such as CATL and BYD, are at the forefront of efforts to commercialise new battery chemistries such as sodium-ion and solid-state.

Industrial energy efficiency has represented a much higher share of patenting in China since 2010 than in the rest of the world. When combined with other energy efficiency technology categories, China's focus on energy efficiency in general has played a very large role in the rise of low-emissions energy patenting in general. This energy efficiency focus, as China's advanced manufacturing and heavy industry sectors sought to weather stiff competition at home and compete in export markets, took over from fossil fuel supply – including mining, oil refining, processing and downstream technologies – as a driver of patenting in China around 2002.

In the United States, the technology shares have reshuffled following a swell in fossil fuel patenting that coincided with the rise of unconventional oil and gas production up to 2014 – an industrial boom that was based on newly applied technologies such as horizontal drilling and hydraulic fracturing. As oil prices slumped in 2015, the incentives to innovate and patent also receded in this sector. Since then, energy storage technologies and energy efficiency or fuel substitution in industry have emerged as larger areas of innovation, representing more than one-third of energy-related patenting activity in the country from 2021 to 2023. Over the same period, hydrogen and fuel cell technologies declined from about 12% of US energy patenting in 2000 to roughly 5% in 2023. Growth in these two areas echoes the pattern seen in China, although to a far smaller extent. While energy storage technologies accounted for more than 40% of energy patenting worldwide in 2023, they represented just 20% of energy patents in the United States.

The trend towards very high shares of energy storage patenting is most pronounced in Japan. In 2023, energy storage accounted for more than 70% of all energy patents, showing higher specialisation in a single field than for any other countries and regions analysed. The growth has been rapid, from a share of around just 20% of energy patenting in 2015 to 10% of all Japan's patenting across all technologies (including those unrelated to energy) in 2023. At the same time, Japan's share of energy technology IPFs related to electric mobility technologies has shrunk to 5% of energy patents in 2023, down from a high of 32% in 2011.

Energy patents by technology in the United States, Japan and Europe, 2000-2024e

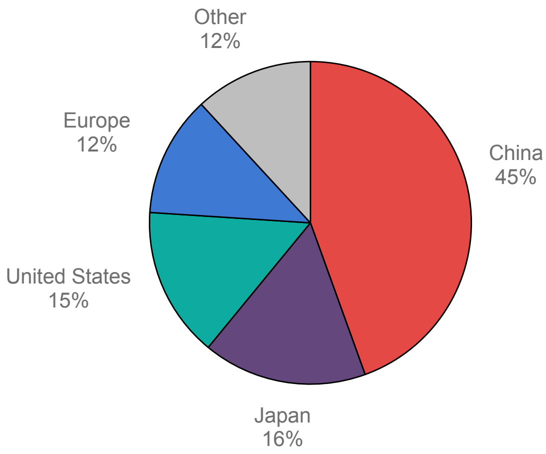


Notes: "Other low-emissions" includes aviation, rail, marine, bioenergy, carbon capture and storage, electricity grids, nuclear and renewables (including those integrated into buildings). "Other energy efficiency" includes agriculture, buildings, road transport. Based on international patent families (IPFs), each of which represents a unique invention and includes patent applications filed in at least two countries. 2024e: estimated. It is very preliminary and only includes a low share of IPFs that will eventually enter the dataset for that year. Technology categories follow Y02-Y04S scheme for low emissions technologies (i.e. energy storage includes Y02E 60/10-16 and Y02E 70/30) and IEA and EPO methodology for identifying fossil fuel technologies in patent data.

Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

In Europe, the focus of energy innovation has shifted significantly over time. In recent years, energy storage, fossil fuel and hydrogen technologies have emerged as growing fields of innovation. Europe has long been a leader in energy efficiency-related R&D spending and regulation. However, since 2015, just 12% of energy patenting related to energy efficiency has come from Europe, compared with 45% from China, 16% from Japan and 15% from the United States. Electric mobility technologies, which were the primary area of focus between 2016 and 2020, represented only 8% of European energy patenting in 2023. The share of IPFs related to other low-emissions technologies has been relatively stable over the same period, and were mainly dominated by technologies related to aviation, rail and marine transport, as well as bioenergy and technologies for renewable energy integration in buildings.

Share of energy efficiency patents by country or region of invention, 2015-2024



Notes: Based on international patent families, each of which represents a unique invention and includes patent applications targeting at least two countries. The datapoints for 2024 are considered provisional due to the time lag in filing applications in the PATSTAT database. Technologies were categorised according to the Y02 CPC scheme.

Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

National specialisations in energy technologies

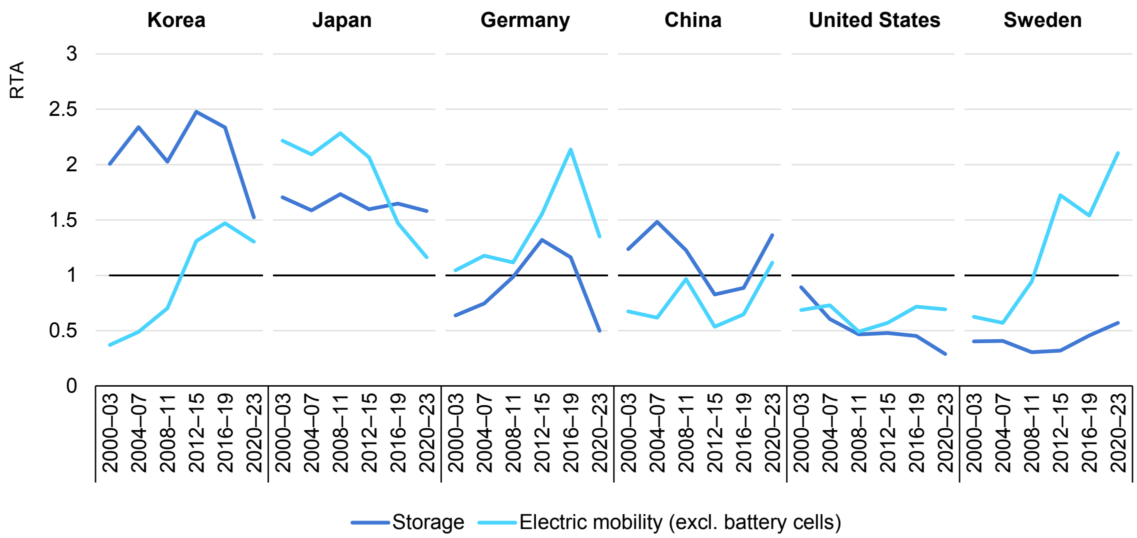
A more detailed picture of relative country-level specialisations in different energy technologies can be developed by using the revealed technology advantage (RTA) index. This indicator reflects the country's relative patenting activity in that technology compared with its overall innovation output and also to global innovation levels in the same technology. As an indicator of specialisation, it relates to all sectors combined and not just among energy technologies. An RTA of one means that a country's share in a technological field equals its share in all technological fields. The index is equal to zero when the country holds no patents in that field.

For example, Korea has the most specialisation in energy storage and electric mobility (highest combined RTAs), though its absolute patenting is lower than that of China and Japan, which submitted nearly 35 000 patents together in storage from 2020 to 2023. Korea's national policy emphasises energy storage technologies and has supported a vibrant private sector for battery R&D and production.

Comparing countries' RTA values in energy storage and electric mobility shows a correlation with the countries that are most active in battery and EV manufacturing. This supports the case for a virtuous cycle of innovation generating first-mover advantages, then continuous R&D at the technological frontier and learning-by-doing (through manufacturing) underpinning further investment in manufacturing expansions. However, the trend for Korea, Japan and the United States has been towards lower specialisation in these technology areas over recent years. The United States shows no strong specialisation in storage nor in electric mobility.

Germany and Sweden have shown increasing specialisation in electric mobility, reflecting the importance of the car industry to their economies. China, however, has RTAs closer to one in these areas, which signals that they are still not a large share of overall patenting in China, despite some signs of rising specialisation in the past few years.

Revealed technological advantage in energy storage and electric mobility in selected countries, 2000-2023

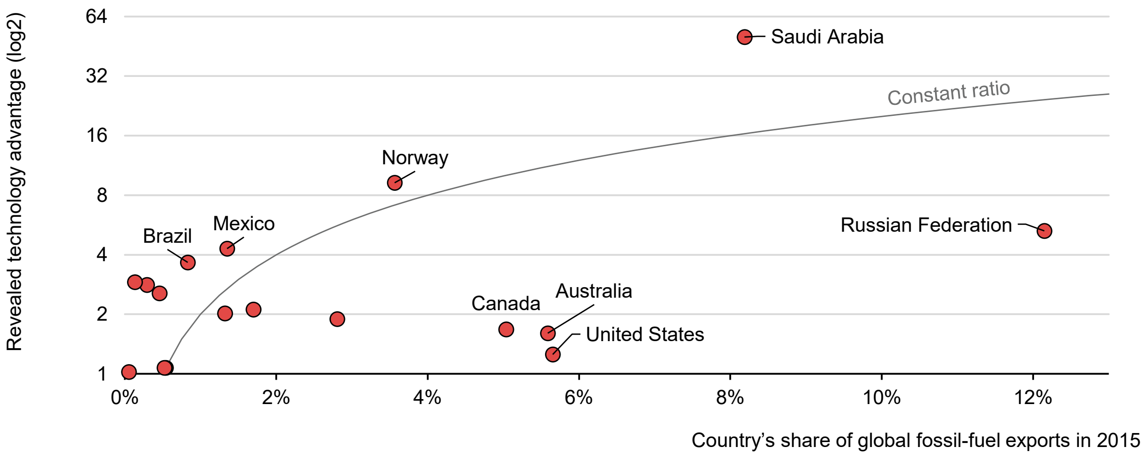


Note: RTA = Revealed technology advantage.
Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database). Technologies were categorised according to the Y02 CPC scheme. Storage includes Y02E 60/10-16 & Y02E 70/30.

Countries' RTAs are often related to their main areas of economic activity, in some cases based on their natural resources. For example, Saudi Arabia, which accounted for 8% of global fossil fuel exports in 2015, has the highest RTA of any country in the area of fossil fuels. Here, the directionality of innovation is clear: Saudi Arabia is not a leading oil producer because it started as a leading innovator in oil technologies but rather has sought to maintain technological leadership in an industry in which it has a natural advantage. In addition, the presence of cutting-edge technology in a country's leading sectors generates new ideas and spurs R&D projects to explore them because the market pay-off of a more effective technology is evident.

Due to these "induced innovation" dynamics, fossil fuels represented 75% of Saudi Arabia's energy patenting in 2023 Similarly, the Russian Federation (hereafter "Russia"), which accounts for 12% of global exports, is relatively specialised in fossil fuels. Australia, Canada, and the United States, with more diversified economies, are less specialised in fossil fuel technologies. Norway, on the other hand, has a technological specialisation in fossil fuels that exceeds what might be expected by its 3.5% share of fossil fuel exports, suggesting that its technical capabilities enable technology exports.

Revealed technological advantage in fossil fuels, 2020-2023, and share of global fossil fuel exports, 2015

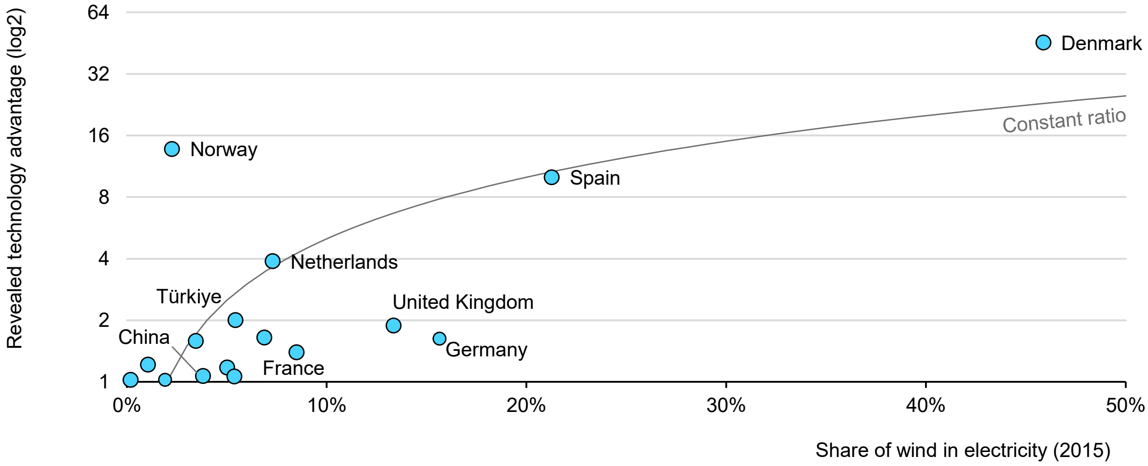


Notes: For this analysis, an RTA value was generated per country and smart grid technology over a four-year range for selected countries. Fossil fuel export shares are calculated on an energy content basis using gross export figures. Technologies were categorised according to the Y02 CPC scheme.

Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

Turning from fossil fuels to wind energy, similar dynamics appear to hold firm. The countries with the highest technological specialisations today are those that adopted wind energy earliest and fastest. Denmark had a 50% wind energy share in its electricity mix by 2015 (it rose quickly from a share of 3% in the early 1990s and is now around 60%), while Spain had 21% and the Netherlands 7%. By 2020-2023, these countries had maintained high specialisation in wind technologies, with RTAs of 46, 10 and 4, respectively. Despite having recently become a major manufacturer of wind turbines, China had a relatively low wind electricity share in 2015 (4%) and an RTA close to one between 2020 and 2023. Norway's relatively high specialisation in wind energy may be a sign of the strength of technological spillovers for helping countries enter sectors in which they do not have large domestic industries. Many offshore wind technologies share similarities with offshore oil and gas techniques and Norwegian public research funding has supported wind energy R&D due, in part, to these synergies.

Revealed technological advantage in wind energy technologies by country, 2020-2023, and share of wind in electricity, 2015



Note: Technologies were categorised according to the Y02 CPC scheme.
Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

Trends in selected technology areas

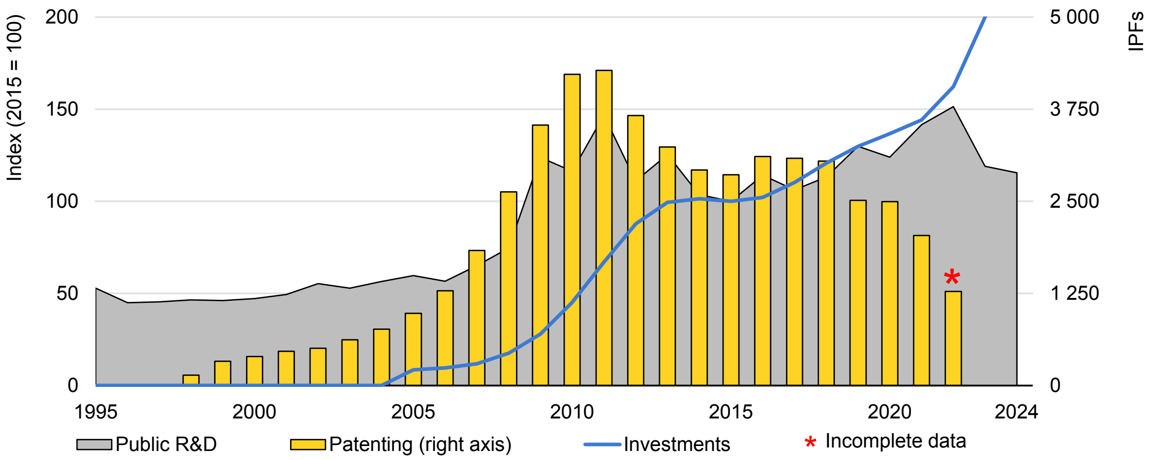
Strong patenting activity not only reflects technological progress but also demonstrates a growing desire by companies and countries to protect their innovations and secure strategic advantage. This demonstrates confidence in emerging technologies and highlights increasing competition to lead the next generation of technology solutions for the energy sector. Combined analysis of spending trends and patenting data for technologies that are now gaining an increasing market share, like solar PV, batteries or EVs, can pave the way for the development of criteria to identify areas that are well on their way to bringing promising technologies to market.

Solar PV

No single other energy technology received as much investment in 2025 as solar PV. Globally, it is a major industrial sector and has become a major source of power generation: investment in solar PV more than tripled from USD 140 billion in 2015 to USD 440 billion in 2025. This growth is based on technology innovation, and several decades of R&D that preceded it. When there were only limited near-term expectations of revenue from solar PV sales before 2000, public R&D spending was consistent and patenting was very low. As R&D began to deliver products closer to commercial requirements and market opportunities – typically supported by government policy – R&D spending rose and then patenting grew to a peak of more than 4 000 IPFs in 2011. Investment duly followed, with a steep upsurge mirroring the rise of patenting 3 years previously.

This patenting peak coincides with both the aftermath of the financial crisis and consolidation within the solar PV sector around a dominant crystalline silicon design. Competitive edge has come to be defined by scale and manufacturing excellence rather than PV design innovation. Although innovation continues, solar PV patenting fell back after 2011.

Patents, R&D expenditures and total investments for Solar PV, 1995-2023

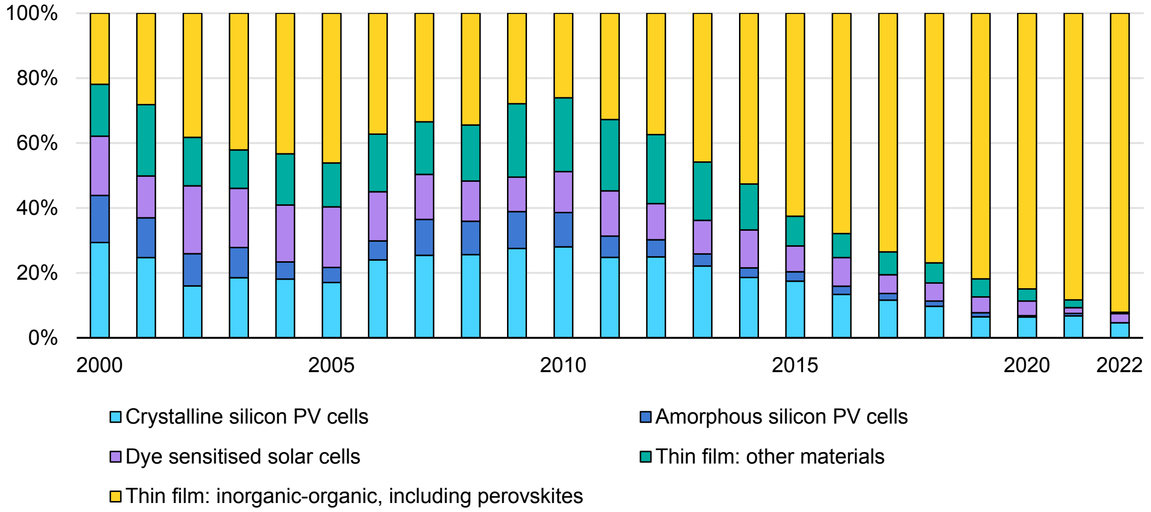


Notes: IPF = international patent family. Patent data stops at 2022 while deployment and R&D spending are reported until 2024. Patenting data for 2022 is incomplete.
Source: IEA analysis based on December 2025 data from the European Patent Office (EPO).

The changes in solar PV innovation before and after 2011 are visible in the sub-categories of patenting by cell type. Before solar PV was widely adopted there was significant diversity of designs being patented in the hope of scaling them up for market returns. It was not apparent from patenting activity in 2000-2005 that crystalline silicon would win the first phase of the solar technology race, yet thanks to its ease of manufacturing at scale and subsequent cost advantages, it now accounts for 98% of all solar PV modules sold worldwide. Its share of patenting increased from 2005 onwards, becoming the largest field of solar PV patenting in 2010.

Since 2011, the race for technological leadership has shifted in favour of one technology: perovskites. Perovskites can achieve higher efficiencies and take up less space than crystalline silicon modules. Following many years of innovation, they have recently emerged as a favourite to be successfully scaled up at competitive prices, whether in pure perovskite cells or in tandem with silicon cells. This has led to a ramp up of patenting, following a lull in 2005-2010: perovskites represented more than half of all solar PV cell material patenting in each year since 2016. Other materials, such as other thin film PV cells, which represented more than 10% in 2000, have since fallen out of favour: no IPFs related to this material have been filed since 2019.

Share of solar PV patents by material, 2000-2022



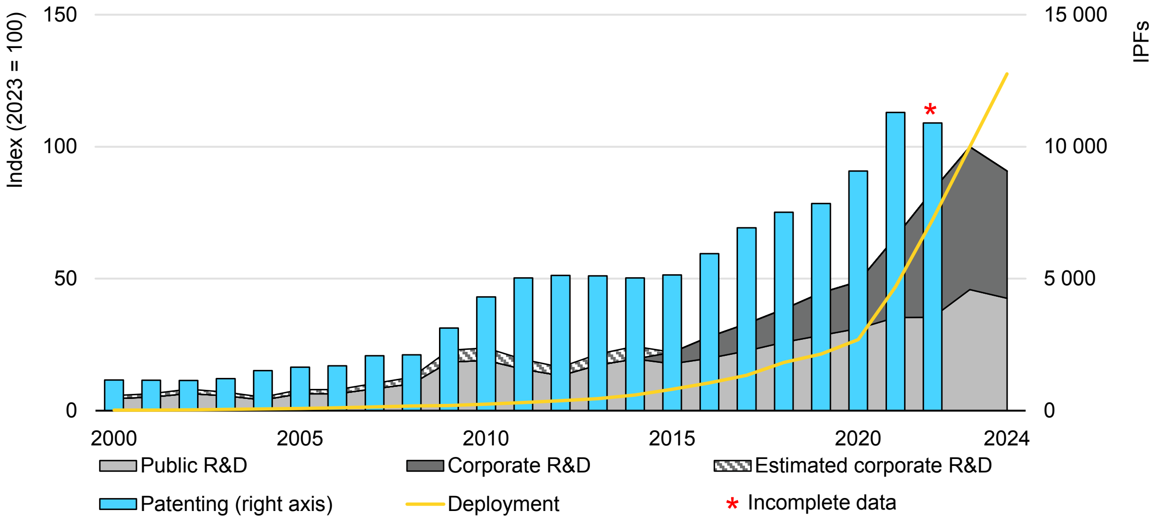
Note: Based on international patent families.
Source: IEA analysis based on December 2025 data from the European Patent Office (EPO).

Lithium-ion batteries

Patenting activity for batteries first accelerated in the 2010s, similarly to solar PV, and then again after 2015. In the early stages, battery R&D spending was largely public. Since 2015, battery markets have entered a period of sustained growth, which accelerated after 2020, driven by rising EV deployment. This expansion has created new opportunities but also new requirements – batteries originally designed for portable electronics needed to be adapted for EVs, which prompted significant R&D efforts and patenting activity. Corporate R&D spending surged as a result, surpassing public R&D spending from 2022 onwards.

Lithium-ion batteries now dominate deployment in EVs, battery storage systems, and portable electronics – and they lead patenting activity as well. Patents related to lithium-ion chemistries and designs have accounted for 50-60% of all battery patents submitted annually since 2000, with an additional 30-40% linked to battery manufacturing, largely focused on lithium-ion production. Other battery types represented less than 10% of patents in 2022, down from about 15% in 2000. Renewed interest in alternative chemistries such as sodium-ion and redox-flow batteries could reverse this trend, although lithium-ion is expected to remain the market leader in the coming years.

Number of international patent families, R&D expenditures of rechargeable batteries and lithium-ion battery deployment, 2000-2024



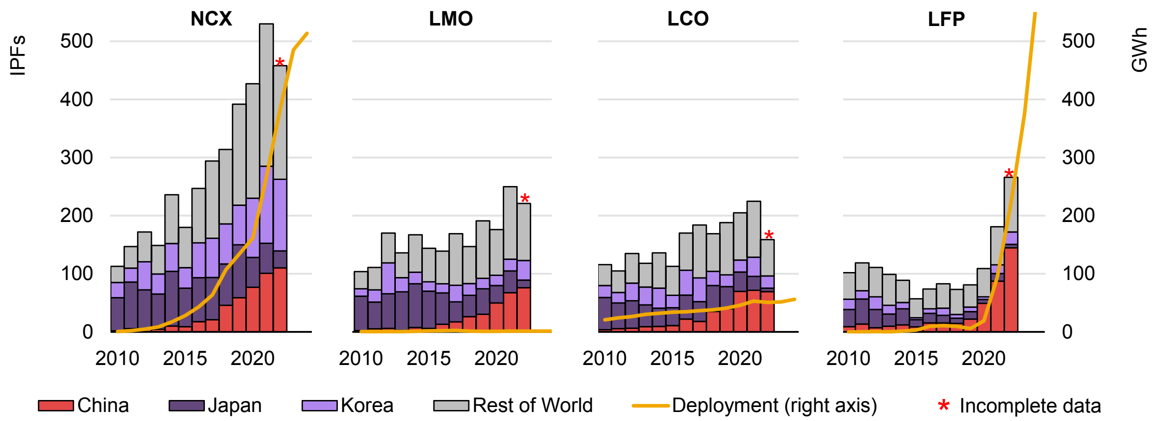
Notes: IPF = international patent family. IPFs are based on fractional counts. Public R&D includes spending on road transport electrification. Corporate R&D spending before 2015 (dashed) is estimated by applying the same public-to-private spending ratio observed in 2015. Deployment refers to lithium-ion batteries, and includes electric vehicle batteries, battery storage systems, portable electronics, and other applications, such as electric bikes and drones. Patent data stops at 2022 while deployment and R&D spending are reported until 2024. Patenting data for 2022 is incomplete.

Source: IEA analysis based on December 2025 data from the European Patent Office (EPO) and Bloomberg.

Behind the sustained growth in lithium-ion battery deployment, innovation efforts have been directed to different cathodes over time. Until 2022, the latest year for which data is available, the largest share of efforts was directed to nickel-based cathodes, such as lithium nickel manganese cobalt oxide (NMC). By 2015, NMC was the most widely used battery chemistry in EVs, following the use of lithium cobalt oxide (LCO) and lithium manganese oxide (LMO) cathodes during the early stages of the industry's development. However, as has been widely noted elsewhere, rapidly growing adoption of the cheaper lithium iron phosphate (LFP) cathode chemistries since 2020 has spurred innovation, taking it to second place among cathode chemistries by patenting activity in 2022. LFP deployment has grown rapidly too – in 2024, LFP accounted for about half of EVs sold globally, largely driven by deployment in China, and over 90% of stationary storage installations. By contrast, anode materials have been less diversified, with graphite remaining the dominant choice, though graphite-silicon blends are gaining market share.

China, Korea and Japan remain the leading sources of lithium-ion battery patents, though their relative contributions have shifted markedly over the past decade. In 2010, Japan generated almost half of all cathode-material international patent families; by 2022 its share had fallen to about 5%. Over the same period, China's share rose from less than 5% to more than 35%, reflecting broad patenting activity across all major cathode chemistries. China has led innovation in LFP technologies since 2019, as well as driving their rapid commercial deployment.

Number of international patent families and deployment per lithium-ion battery cathode active material by region, 2010-2024



Notes: IPF = international patent family; NCX = lithium nickel cobalt manganese oxide (NMC) and nickel cobalt aluminium oxide (NCA); LMO = lithium manganese oxide; LCO = lithium cobalt oxide; LFP = lithium iron phosphate. LFP refers to lithium-ion batteries and it includes electric vehicle batteries, battery storage systems, and portable electronics. IPFs are based on fractional counts. Patent data stops at 2022 while deployment is reported until 2024. Patenting data for 2022 is incomplete.

Sources: IEA analysis based on December 2025 data from the European Patent Office (EPO); IEA (2025), Global EV Outlook 2025; IEA (2025), World Energy Outlook; Avicenne Energy.

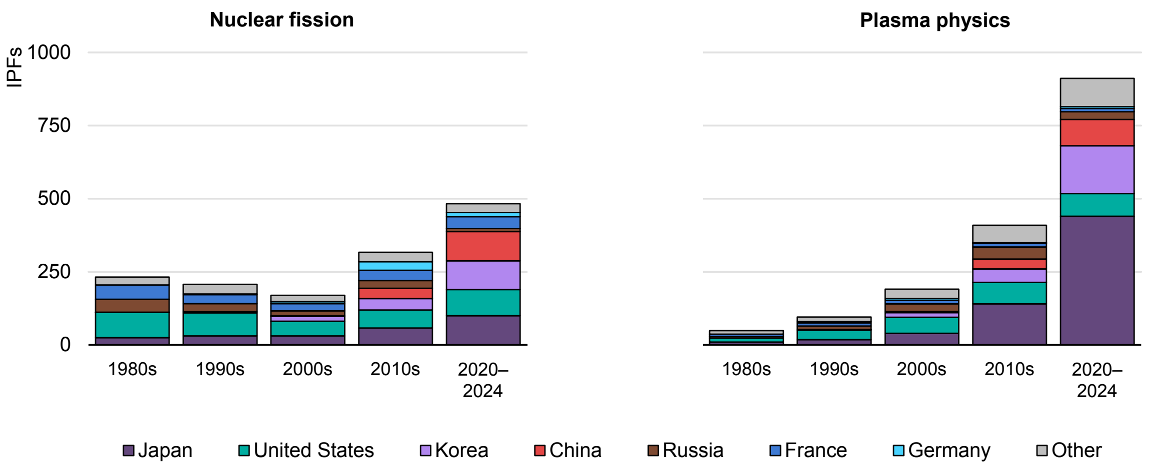
Areas with growing patenting

Patenting data can be explored in search of fields of emerging energy innovation. Given the relationship between patenting and subsequent investment that is seen in the cases of solar PV and batteries, it might be possible to identify tomorrow's high-impact technologies that have not yet led to widespread commercial uptake or hype. In this section we highlight three selected areas that are following a strong patent growth trend. Two of these – nuclear and electricity grids – are covered in detail in the focus chapters of this report, where the drivers for the underlying dynamics are explained in more detail. The third, critical minerals, was covered as a focus chapter in last year's edition, in relation to battery supply chains.

Nuclear fission and fusion

Innovation related to nuclear energy has rebounded from a low point in the 1990s and early 2000s, driven up by both nuclear fission research and work on fusion energy. For nuclear fission, patenting has risen above the rate seen in the 1980s, a period when nuclear fission accounted for more than 50% of IEA Members' public spending on energy R&D. For fusion energy, a shift in the nature of R&D – from mostly testing scientific principles to also working on the engineering challenges of commercialisation, including in private companies – has steadily pushed up the rate at which inventors are protecting their ideas for commercial exploitation.

Average annual patenting in nuclear fission and fusion, by country, 1980-2024



Notes: IPFs = international patent families, based on fractional counts. Categorisation of technologies by IEA experts. 2020-2024 data is nowcasted based on historical data with a variable factor for main patenting countries and a fixed factor for the rest of the countries. The plasma physics category encompasses all related R&D and therefore includes non-energy applications.
Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

However, while both these areas appear to be more actively innovating, the absolute numbers of international patent families are relatively low compared with other energy technology areas. A possible reason for this in the case of nuclear fission is that the sector remains dominated by small number of large firms with similar know-how and limited competition from new entrants due to the high cost and regulatory barriers to entry in the market for large reactors. This situation, combined with reliance on the expertise of third-party firms for much of the construction work, reduces the incentives to patent minor design modifications. In addition, regulatory approvals for nuclear fission technologies are costly and take time, which has typically led to the development of a full new reactor design each decade or two, and few modifications between major design revisions. This will be less true for fusion energy as it evolves in its first near-commercial forms: safety regulations are likely to be less stringent and more inter-firm and international competition to secure first-mover advantages is apparent. Patenting in the area of fusion energy can be expected to rise further.

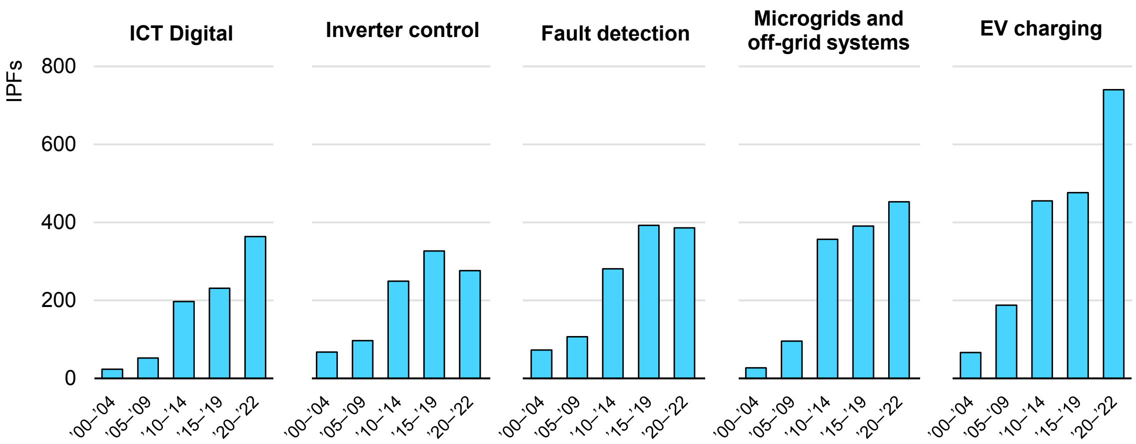
Regionally, the landscape of nuclear patenting has evolved. In the 1990s, the United States was the largest patentor of nuclear fission inventions and most patenting was from a handful of countries developing so-called Generation II and

Generation III/III+ reactors (United States, Japan, France and Russia). However, this period coincided with a slowdown in the global deployment of nuclear power, which has only recently been reversed. Investment in new nuclear plants doubled between 2018 and 2024, with Korean and Chinese companies playing a major role in construction of these new reactors at home and abroad. In parallel, there has been growing enthusiasm in the past decade for smaller reactors, which promise stable power output and low-emissions nuclear power with more manageable project investment budgets and greater standardisation. Research activity related to small modular reactors is more geographically diverse and involves more smaller private nuclear firms with high incentives to patent. In recent years, China has been the highest nuclear fission patentor, with Korea, Japan and the United States also making notable contributions.

Electricity grid technologies

There are a range of ways in which technology innovation can play a role in addressing some key challenges facing electricity grid operators. As these challenges have become more apparent to grid operators, their equipment suppliers and public researchers, patenting in all the areas has risen steadily. As described in Chapter 6, today's commercial availability of several important technologies that are expected to help facilitate an affordable transition to more inverter-based, flexible and resilient grids is the product of far-sighted innovation since the early 2000s.

Global patenting trends in selected electricity grid technology areas, 2000-2022



Notes: ICT = Information and Communication Technologies; EV = Electric Vehicle; IPFs = international patent families, based on fractional counts. The post-2020 data is underestimated (not nowcasted).

Sources: IEA (2024), Patents for Enhanced Electricity Grids report and IEA analysis based on December 2025 data from the European Patent Office (EPO).

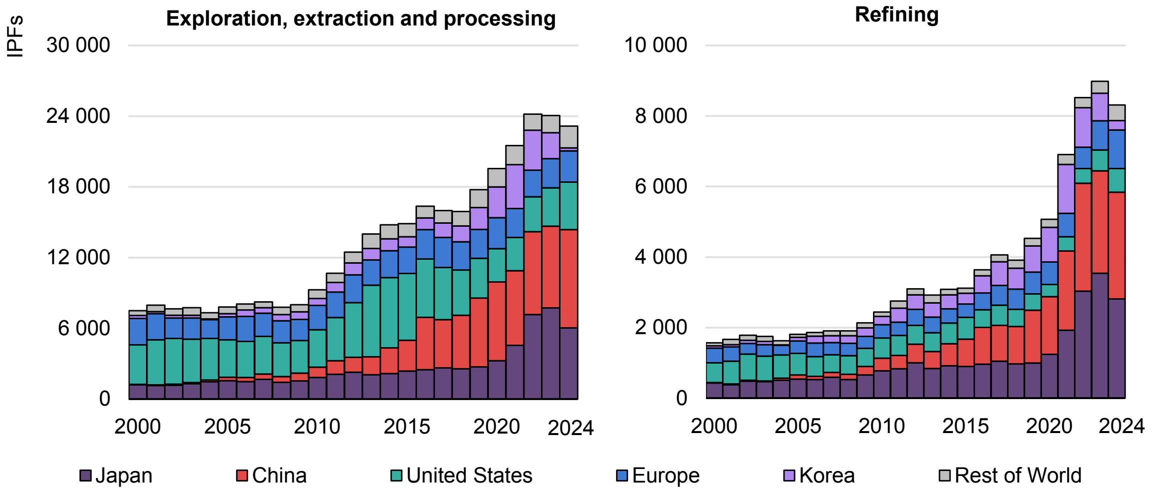
Since 2000, the overall trend in grid-related patenting has been influenced by geographical and technological changes. Regionally, the period can be split into a phase of patenting growth up to 2013, followed by a dip and resurgence since then. In the first phase, Japan, the United States and Europe led the activity, and there was notable growth in the early 2010s in the area of EV charging systems as suppliers sought a market stake during a period of standardisation. After 2015, growth has been driven largely by China, which continues to expand and modernise its power networks. Recent electricity grid patenting is more concentrated in technologies that are directly relevant to preventing cascading faults that can lead to system-wide outages: inverter controls, microgrids, off-grid systems and tools for managing flexible demand (especially the management of EV charging and using vehicle batteries as a grid resource). Digital technologies for fault detection and management of grid information and communication are also strong growth areas, boosted in recent years by the application of new AI techniques.

Critical minerals

While not fully included in our scope of energy technology patenting, investigation of patenting for critical minerals production shows it to be a significant and growing area. It reached around 33 000 IPFs in 2023, up from around 13 000 in 2010, a level that had been relatively stable since 2000. These IPFs cover exploration, extraction, processing and refining technologies for a set of minerals that are important for today's energy sector, and for expected changes in the energy system, such as the increased use of advanced batteries and electrification of end-uses.[6] This increase in patenting activity can partly be attributed to the value governments place on extracting and processing these minerals in places with the lowest concerns over trade disruptions and the maximum domestic economic benefits. Technology could play a large role in efforts to source minerals from alternative locations, as new techniques will be required to make competitive certain resources that have not previously been economically attractive – including geothermal brines, mine tailings and end-of-life products.

[6] Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance. Rare earth elements are essential for permanent magnets used in wind turbines and EV motors. Electricity networks also need a huge amount of aluminium and copper, the latter of which is the cornerstone of all electricity-related technologies.

Global patenting trends in critical mineral technology areas, 2000-2024



Notes: IPFs = international patent families, based on fractional counts. As a first attempt, the IEA defines critical minerals sectors using CPC classifications combined with targeted keywords, covering extraction, processing and materials technologies as well as digital and automation applications linked to critical minerals, beyond the traditional energy sector. 2020-2024 data is nowcasted based on historical data with a variable factor for main patenting countries and a fixed factor for the rest of the countries.

Source: IEA analysis based on European Patent Office PATSTAT patents database (Spring 2025 edition accessed through the OECD Micro-data Lab: Intellectual Property Database).

Most patenting in this area is for technologies relating to the exploration, extraction and processing of energy-related critical minerals. This may be a reflection of greater international interest in ways to unlock mineral resources in alternative locations, compared with interest in improving the efficiency of refining those minerals. However, patenting of refining technologies has been growing fastest, led by China and Japan, with innovators in these countries seeking to gain a competitive edge in the production of refined manufacturing inputs from a range of raw material sources. The rising presence of Japanese inventors in these areas, in which they do not have major domestic production facilities, likely reflects the efforts of major Japanese battery to manage their supply chains and stay competitive. As shown earlier in this chapter, battery innovation represents a large share of Japan’s energy patenting. In the areas of exploration, extraction and processing of critical minerals, US patenting has reduced its share of total IPFs from around 40% to less than 20% in the past decade.

In terms of the minerals cited in patent applications, there are no striking differences. The most frequently cited are lithium, cobalt and rare earth elements, though many patented techniques are applicable to multiple minerals.

Chapter 4. Policy progress

Energy innovation policy sits at the intersection of energy and industrial strategies, shaping how governments steer technological change across the energy system. As the fruits of R&D emerge as new products and as markets evolve, policy makers reassess the mix of policy instruments they deploy and the sectors they prioritise. The changes in energy innovation policy reported in this chapter reflect the close connection between energy innovation and wider policy goals, including economic growth, energy security, emissions reductions and energy affordability as well as positioning domestic innovators to compete in global markets.

Building on the IEA Energy Innovation Policy Guide, this chapter presents a selection of policy updates from 2025 covering 32 countries and jurisdictions, by type of measure, drawing on findings from the expert survey conducted for this report.[7] More than 80 new policies are included, as well as over 60 examples of actions taken under existing policies. It contains a wealth of examples of how governments are adjusting their policy portfolios in response to changes in the technological, economic and political landscape. They do so while seeking to balance the twin imperatives of providing stable and patient funding for long lead-time innovation, while also being flexible to grasp new opportunities, especially for fast-growing manufactured and digital technologies. The chapter concludes with reflections on progress against the policy priorities described in The State of Energy Innovation 2025.

Taken together, energy innovation policy updates from 2025 reflect several main themes:

- **Policy interventions that enhance industrial competitiveness are in the foreground.** Energy innovation policies are increasingly shaped by a mix of policy objectives, and while emissions reduction dominated the policy narrative a few years ago, considerations related to industrial competitiveness now feature more strongly in policy design. Competitiveness is at the core of new programmes such as the United Kingdom's Clean Energy Superpower Mission and Canada's Climate Competitiveness Strategy. The European Union is proposing an EU Competitiveness Fund and making competitiveness a central objective of its Horizon Europe (2028-2034) programme, with clean transition framed as a contributor to this goal. Industrial competitiveness, economic growth and job creation provide the case for supporting energy technology manufacturing. Examples include Australia's Future Made in Australia Fund and the EU Net Zero

[7] Policies presented in this chapter represent new policy approaches, reorientations towards emerging technologies or notable initiatives in countries without a strong legacy of energy innovation policy, where fiscal constraints play a larger role.

Industry Act (NZIA), which allows domestic production to be prioritised in EU renewable energy auctions for the first time.

- **Supply chain resilience is a priority**. Energy innovation is a part of strategies to limit exposure to supply disruptions and associated costs, especially in relation to critical minerals, which are unevenly geographically distributed and also relevant to digital and defence technologies. Notable examples of policies aimed at strengthening innovation in national critical mineral supply chains include the new Office of Critical Minerals and Energy Innovation and new grants under the Advanced Research Projects Agency–Energy (ARPA-E) in the United States and Natural Resources Canada Science and Technology Strategy 2025, which targets both energy and mineral security.
- **Electricity security and grid resilience needs are calling attention to long-duration energy storage**. In 2025, several governments introduced or expanded support programmes, including China's Special Action Plan for Large-Scale Construction of New Energy Storage (2025-2027), the UK Long Duration Electricity Storage cap and floor scheme, and Italy's Energy Services Capacity Storage Mechanism for long-duration storage contracts.
- **New approaches to low-emissions hydrogen and carbon dioxide removal (CDR) are being promoted as part of long-term industrial strategies**. Although progress has been slower than expected, these sectors are still receiving policy attention and support. Examples include the first contracts awarded through Japan's Contracts for Difference (CfD) scheme under its Hydrogen Society Promotion Act, the inclusion of carbon capture, utilisation and storage (CCUS) in the 2026 round of Germany's Climate Protection CfD, the launch of the third EU Hydrogen Auction under the Innovation Fund, and China's first batch of National Hydrogen Pilot Projects.
- **A race to develop commercial fusion energy is spurring new strategies and funding**. While public support for international collaboration on fusion energy continues, such as for ITER, recent initiatives reflect a shift towards domestic commercialisation roadmaps and projects. Key initiatives in 2025 include the US Fusion Science and Technology Roadmap, establishment of the China Fusion Energy Company, the EU Moonshot proposal on fusion energy, the fusion focus under the United Kingdom's Modern Industrial Strategy and Germany's fusion Action Plan (see Chapter 7 for more details).
- **Governments seek to foster the use of artificial intelligence (AI) to accelerate energy technology innovation**. As highlighted in The State of Energy Innovation 2025, AI for innovation is a third pillar of energy and AI policy, alongside energy supplies for AI and AI for optimising energy use. Policy examples include a new Office of Artificial Intelligence and Quantum and an AI-Fusion digital convergence platform in the US Department of Energy, a new AI funding stream in the Canadian Energy Innovation Program and Morocco's Jazari Institute for, among other things, AI and energy innovation. Dedicated efforts in partnership with the private sector also focus on using AI to power new discoveries, including in Canada, the United Kingdom and United States.

- **Governments are seeking to make funding and advisory services more accessible.** The purpose is to help innovators navigate an increasingly complex landscape of policy and funding support. The European Union has increased funding for the InvestEU Advisory Hub and renewed Project Development Assistance for Innovation Fund applicants, and the European Investment Bank has established the TechEU Platform, a one-stop-shop to streamline access to a range of financial instruments.

Overarching energy innovation strategies

Many countries and regions set out strategic visions for R&D priorities and innovation objectives, which are typically renewed at regular intervals. Energy innovation strategies may be embedded in broader science, technology and innovation strategies, exist as a stand-alone strategy, or focus on a single energy technology. Overall, energy consistently ranks as a top priority in strategic innovation plans. Energy innovation may also feature in broader industrial strategies, such as Germany's High-Tech Agenda and the United Kingdom's Modern Industrial Strategy. Energy innovation strategies can help prioritise investments, reduce policy uncertainty by identifying strategic areas, create common expectations among diverse stakeholders and establish measurable goals and performance metrics for accountability.

Selected new or updated strategies relevant to energy technology innovation, 2025

China

China's 15th Five-Year Plan will set the country's strategic direction for 2026-2030. Although the plan has not yet been formally released, preparatory documents indicate a focus on emerging energy technologies including fusion energy, hydrogen and energy storage. It also emphasises venture capital and risk sharing mechanisms.

European Union

In July 2025, the European Commission published its proposal for the next Horizon Europe R&D Framework Programme, outlining a plan to double the 7-year budget for research and innovation to around USD 190 billion for 2028-2034. Clean aviation, automated transport and fusion energy are among the proposed "moonshot" projects.

A new governance model for the Strategic Energy Technology Plan was adopted to give a greater role to member states in setting priorities, targets and milestones.

Germany

The High-Tech Agenda is an innovation strategy that aims to invest approximately USD 19 billion by 2029, targeting strategic technology sectors, including energy. Key focus areas include fusion energy, "climate-neutral energy" (with emphasis on geothermal and hydrogen), and "climate-neutral mobility". The strategy shifts public R&D support toward performance-based funding linked to defined milestones.

Indonesia

Government Regulation No. 40/2025 updates Indonesia's National Energy Policy, targeting net zero emissions by 2060 and prioritising energy security. It expands the definition of "new energy" to include hydrogen, ammonia and nuclear, each with specific quantitative targets, and incorporates local content provisions, including requirements for technologies developed domestically.

Italy

The Italian Electrical System Research Three-Year Plan 2025-2027, funded by an electricity tariff levy and a total budget of around USD 260 million, pursues two core objectives – decarbonisation and grid evolution and digitalisation – and introduces new research topics on bioenergy and the impacts of renewable energy on water.

Japan

The Integrated Innovation Strategy is an annual cross-ministerial publication. The 2025 edition highlights fusion energy as a key field and establishes a Cabinet Office taskforce for the update of its Fusion Energy Innovation Strategy. The energy section builds upon the 7th Strategic Energy Plan, under the principle of S+3E (Safety, Energy Security, Economic Efficiency and Environment), emphasising energy efficiency, renewable and nuclear power, grids, low-emissions fuels and CCUS.

Korea

Korea launched the K-Moonshot Project to support "high-risk, high-reward" R&D with a legal requirement for at least 10% of government R&D to be allocated to basic research. It will reorganise public research institutes around national missions and set performance-based incentives for research teams. Energy is a priority, including a next-generation small modular reactor (SMR) promotion strategy with around USD 825 million to build a private-led SMR ecosystem by 2030, and a programme to design a fusion energy demonstration reactor in the 2030s.

Switzerland

The Swiss Energy Research Master Plan 2025 to 2028 is the federal energy research masterplan setting public R&D budgets and guiding national and sub-national research activities. Priority areas include system flexibility, sector coupling and digitalisation, energy storage, heating and cooling, CCUS, and negative emissions technologies.

United Kingdom

The UK Modern Industrial Strategy, a 10-year plan to raise private investment, was published in November 2025. It emphasises simplifying regulatory and permitting processes for innovators. The associated Clean Energy Industries Sector Plan identifies wind, fusion energy and fission, CCUS, hydrogen and heat pumps as priority technologies. In October 2025, the Clean Energy Superpower Mission identified nine R&D priorities, including energy storage, flexible demand, supply-side flexibility, offshore wind, end-use electrification, low-carbon fuels and CCUS. The United Kingdom will launch Cleantech Innovation Challenges in 2026 in partnership with the private sector.

A reorientation of energy innovation policies in the United States

Several energy innovation policy changes have been enacted or signalled since the new US administration took office in January 2025. The main thrust of these changes is to reorient technology priorities towards certain areas, such as critical minerals, electricity grids, geothermal, nuclear fission and fusion, and AI. A broad outline is provided in the Executive Order Unleashing American Energy, while subsequent Executive Orders provided more detailed guidance.*

- **Critical minerals**. In line with the US ambition to be a leading producer and processor of minerals, including rare earth elements, the government has created a new Office of Critical Minerals and Energy Innovation. New grant programmes include Mine of the Future (USD 95 million), the Rare Earth Elements Demonstration Facility Program (USD 134 million), and the Critical Minerals and Materials Accelerator to pilot technologies such as direct lithium extraction, and the refining or alloying of gallium, gallium nitride, germanium and silicon carbide (USD 50 million).
- **Geothermal**. In the new Hydrocarbons and Geothermal Office at the Department of Energy, geothermal has been elevated alongside conventional energy resources, and next-generation geothermal is now eligible for clean electricity tax credits.
- **Nuclear fission.** A USD 900 million grant programme to support first pilot projects for Generation III+ light-water SMRs was reissued. An Executive Order introduces ways to accelerate test-phase approvals, for example by enabling reactor designs to be tested outside the Nuclear Regulatory Commission (NRC) procedure. Similarly, the Fuel Line Pilot Program does not provide funding but allows fuel-fabrication to be licensed outside the NRC process.
- **Fusion energy.** A new dedicated Office of Fusion was created and a Fusion Science & Technology Roadmap published with a focus on commercialisation. USD 134 million in grant funding was allocated for programmes that foster collaboration between industry, national laboratories and universities.
- **Grids**. With renewed drive towards power network energy security and reliable supplies for data centres, funding was awarded for demonstration projects involving emerging stationary storage technologies through the Critical Facility Energy Resilience programme, previously issued in August 2024.
- **AI**. Launched by Executive Order in November 2025, the Genesis Mission aims to accelerate scientific discovery by establishing an integrated AI platform and a set of major challenges in areas including advanced manufacturing, critical minerals, and nuclear fission and fusion. The new Office for Artificial Intelligence and Quantum aims to enhance workforce productivity and the returns on R&D investment.

For the most part, the refocusing of energy innovation programmes involves continuity of institutions. ARPA-E, which received its first funding in 2009, has issued calls for projects on critical minerals, advanced magnet materials and enhanced geothermal systems in 2025. The Loan Programs Office, operational since 2007, has been re-launched as the Office of Energy Dominance Financing, without emissions reductions requirements, and finalised loans and loan guarantees in Q3-4 2025. In other cases, paused programmes have been re-launched, such as grants for nuclear and storage projects. Some existing tax credits have been expanded or increased in ways that could support pre-commercial technologies: higher rates for direct air capture of CO_2 with enhanced oil recovery; inclusion of geothermal, including R&D for superhot geothermal; and preservation of credits for energy storage and biofuels. The energy R&D budget approved by the Congress in January 2026 maintains a similar overall funding level while reallocating funding among topics (more money for nuclear and less for energy efficiency and renewable energy).

In terms of institutional updates, the names and functions of the Office of Energy Efficiency and Renewable Energy and Office of Clean Energy Demonstrations were changed.

The market outlook for some other innovative technologies has been weakened, by a series of policy changes. In May and October 2025, several hundred energy innovation projects received termination notices for their financial awards. In addition, changes to tax credits for deployment have affected both established and emerging technologies. Tax credits for wind, solar, EVs and manufacturing have been limited or phased out. Tax credits for clean hydrogen will be phased out quicker. The special tax credit rate for sustainable aviation fuel has been reduced.

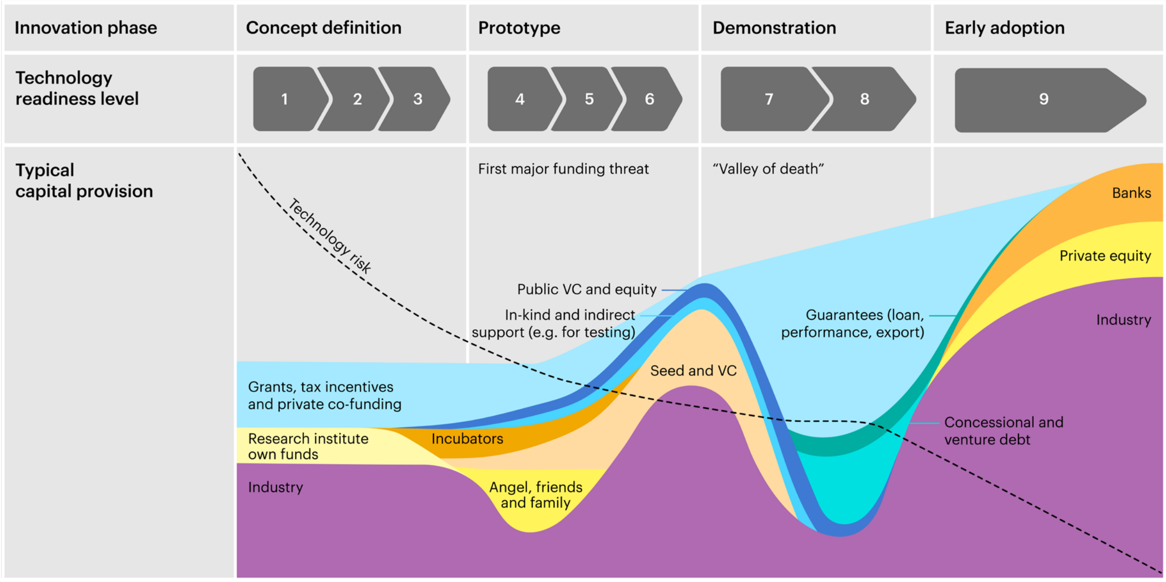
* Executive Orders set direction for the implementation of existing laws.

Direct financial support

Developing new technologies requires sustained investment in research, prototyping, testing, specialised equipment and skilled talent. Because early-stage ideas carry high technical and commercial risk, private markets often do not provide sufficient capital for R&D. On top of this, energy innovation faces unique financial challenges. Energy technologies can take up to several decades to become commercially viable. Reaching the commercialisation stage often requires high upfront capital expenditure due to the reliance on costly physical infrastructure. Energy technologies also depend on complex systems, such as electricity grids, storage solutions, and other complementary technologies, which makes them especially vulnerable to system-level constraints (e.g. grid connection) and co-ordination failures.

These risks and uncertainties, together with the fact that many societal benefits such as emissions reductions, knowledge spillovers and enhanced energy security are not captured in private returns, often lead to underinvestment in energy innovation. Public funding is therefore crucial to bridge this investment gap.

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



Note: VC = venture capital.
Source: IEA (2025) The State of Energy Innovation 2025.

Grants

Globally, grants for energy R&D have been rising in recent years (see Chapter 2). Grants are non-repayable funds typically awarded through competitive calls that define priorities, budgets and evaluation procedures. Most programmes fund individual projects for a fixed period, but some allocate grants over multiple phases. Such multi-stage approaches (sometimes referred to as challenges), fund more projects with smaller amounts in an initial phase then focus larger grants on fewer project teams whose proposed solutions score most highly against criteria.[8]

Governments finance these programmes through a range of sources, including energy levies, carbon pricing, energy company revenues, natural resource royalties or the liquidation of legacy assets. Dedicated earmarking of funds can

[8] While this type of challenge shares some characteristics with inducement prizes (see below), they are a different type of policy measure. Both can take a technology-neutral approach to an emerging policy challenge. However, multi-stage challenges provide grants that fund teams to produce a measurably better solution, whereas inducement prizes only offer funds to teams after they become the first to surpass a set of performance criteria that are fixed upfront.

help build support for fiscal policies such as carbon pricing, and provide long-term R&D budget visibility.

Grants for early-stage R&D

R&D grants are essential because they are often the only viable source of first funding for innovators. Even the earliest ideas require access to labs, equipment and skilled talent. Without this support, only projects with immediate commercial potential would move forward. Grant programmes often encourage collaboration among universities, start-ups and industry, accelerating knowledge exchange.

Selected new or updated grants for earlier R&D phases, 2025

Canada

Canada launched an Artificial Intelligence for Canadian Energy Innovation call under its Energy Innovation Programme. Grants of up to USD 1 million are available for projects to move technologies from early stages (technology readiness level [TRL] 2-6) toward commercial readiness by using AI, for example for materials discovery.

Germany

The Geothermal Exploration Initiative is a new grant programme supporting geothermal projects more than 400 metres deep by funding site-specific studies, geophysical surveys and exploratory drilling, targeting mid-range TRLs and validation in the field.

Ireland

Ireland's Sustainable Energy Authority announced awards of nearly USD 25 million for R&D projects, including offshore wind, synthetic fuels and chemicals, and biogas.

Research Ireland announced an award of USD 2 million from the National Challenge Fund (Energy Innovation Challenge) to the RENEW project on household demand flexibility.

Korea

Three new themes were selected under the Industrial Technology Alchemist Project, with a budget of around USD 45 million over 7 years. The theme "Transcending the Limits of Time and Space in Energy Transfer" targets disruptive approaches, such as superconductors and space-based power generation, to overcome fundamental constraints in energy transfer.

Singapore

The Energy Market Authority launched an Energy Grid 3.0 Grant to support R&D projects on advanced grid management.

Sweden

Three Swedish government agencies launched the "Impact Innovation: Net Zero Industry 2025" call with a budget of around USD 7 million, targeting reduced resource use – including through recycling – and lower emissions in manufacturing and electronics production.

United States

ARPA-E launched six large programmes with a combined budget of USD 215 million (RECOVER, SUPERHOT, MAGNITO, ROCKS, HAEJO, PERSEPHONE). They focus on resource recovery (critical metals and ammonia) from wastewater, geothermal energy from superhot reservoirs, advanced high-performance magnets, rare earth and critical mineral orebody characterisation, deep-water offshore seaweed cultivation, and rapid synthetic-biology engineering of bioenergy crops.

In September 2025, two new Mine of the Future programmes were announced: USD 15 million for national laboratory R&D on domestic critical mineral supply chains; and USD 80 million to test innovative mining-technologies.

Grants to support first-of-a-kind pilots and demonstrations

Grants that support pilot and demonstration projects are usually larger but typically follow similar processes to those for early-stage R&D. Recognising that lengthy timelines from application to final decision can be challenging for start-ups and small and medium-sized enterprises (SME), governments are working to streamline approval procedures (see box below).

Selected new or updated grants for first-of-a-kind pilots and demonstrations, 2025

Australia

A new focus area launched under the Driving the Nation programme has a funding envelope of around USD 65 million for demonstration and deployment of heavy EVs and related charging infrastructure.

The Battery Breakthrough Initiative is a USD 315 million programme offering grants, production incentives or other payments to technologies at TRL 6 or above, targeting battery materials using Australian critical minerals, as well as battery cell production and battery pack assembly.

Brazil

Under the Mais Inovação-Energias Renováveis (More Innovation-Renewable Energy) programme, approximately USD 45 million in grants was awarded to support innovation in low-carbon hydrogen, energy storage, power transmission security and CCUS.

Electricity regulator ANEEL approved five hydrogen R&D projects under the Strategic Call 23/2024, totalling nearly USD 35 million.

Canada

The Critical Minerals Research, Development and Demonstration Program funded several TRL 6-8 projects, including lithium extraction (USD 3.3 million), methane pyrolysis (USD 1 million), nickel recovery (USD 3.5 million) and phosphorus processing (USD 0.5 million).

France

Four sustainable aviation fuel projects received a total of around USD 110 million for engineering studies under the France 2030 – Carb Aéro Programme. In total, the projects target around 270 kt of annual output. They include methanol-to-jet, Fischer-Tropsch and biomass-to-liquids technologies.

India

India announced a USD 11.5 million call for proposals under its Green Hydrogen Innovation scheme for start-ups working on hydrogen technologies, with up to USD 575 000 per project.

Morocco

IBTIKAR AL OMRANE 2025 is a two-phase programme by Al Omrane Group, a public infrastructure firm, and IRESEN, a government energy innovation agency, to advance sustainable construction technologies from TRL 3 to TRL 7. Up to ten teams will receive up to USD 100 000 in total to build prototypes, business strategies and intellectual property strategies in an initial phase; successful projects will move to a second phase with technical assistance from a private sector partner. The USD 50 000 available in the second phase can be repaid or converted to equity.

NATO

The North Atlantic Treaty Organization (NATO) Defence Innovation Accelerator for the North Atlantic (DIANA), launched in 2023, supports civilian innovation with potential defence and security applications. In 2025, DIANA's annual call covered ten challenges, including "Energy and Power", for which 15 start-ups were selected. Selected innovators at TRL 4 or above receive the equivalent of USD 110 000 in a first phase and those chosen for the second phase get access to a further USD 325 000 plus a network of test centres, mentors, investors and market opportunities.

Norway

Two calls were issued and USD 100 million awarded for hydrogen- and ammonia-powered ships under the "Hydrogen in Vessels" and "Ammonia in Vessels" programmes. A new "Bunkering Facilities for Ammonia" scheme awarded USD 41 million for ammonia bunkering infrastructure deployment in Norway. In addition, USD 57 million was awarded for battery systems in ships. From 2026, retrofits of existing vessels that cut emissions by at least 55% will also be funded.

Saudi Arabia

The Saudi Innovation Grant Program issued a first call in 2025 to support start-ups, SMEs and researchers in four national priority areas, including energy, offering grants of up to USD 1.1 million for commercialisation. Several innovation Challenges were also launched, including on domestic uptake of solar energy (thermal and PV) and real-time electricity grid management.

United States

In November 2025, a USD 275 million budget was announced for industrial facilities producing valuable minerals from existing industrial byproducts.

In August 2025, over USD 35 million was awarded to 42 projects to move technologies invented in national laboratories towards market readiness, focusing on grids, AI, nuclear and manufacturing.

For nuclear projects, a USD 900 million solicitation to support the first light water SMRs was reissued, and in December 2025, two USD 400 million grants were awarded to specific projects.

Simplifying access to energy innovation funding

Complex, fragmented funding landscapes can raise barriers for innovators with fewer resources, including start-ups and SMEs. This can lead to missed opportunities to access funding, slower technology development and unnecessary early failure. In 2025, several governments took action to simplify access to support and provide advisory services and help companies and researchers to navigate opportunities more efficiently.

A notable trend in the European Union is the strengthening of advisory services and the goal to simplify funding access, in line with the newly launched EU Startup and Scaleup Strategy. Announcements in 2025 include:

- **InvestEU Advisory Hub:** This central entry point for project promoters seeking advisory support for EU investment funds received additional funds equivalent to USD 43 million.
- **Innovation Fund:** The European Commission and the European Investment Bank (EIB) signed an agreement renewing Project Development Assistance for unsuccessful Innovation Fund applicants, and also making assistance available to aspiring applicants. With an increased budget equivalent to almost USD 100 million (almost 4 times larger than in the prior period), up to 250 projects will receive assistance between 2025 and 2028, with an additional focus on sectors more exposed to EU carbon pricing that are now included in the Innovation Fund's scope, such as buildings and transport.
- **EIB TechEU:** Launched by EIB to support start-ups and scale-ups in cleantech, life sciences and digital technologies, it provides advisory services, financing, and an online Investment Readiness Checker.
- **EU Funding & Me**: A mobile application designed to help applicants navigate different EU funding programmes.

Innovation Canada offers a "one-stop shop" to guide innovators to federal support programmes. In 2025, it published a dedicated guide for clean energy and environmental technologies support.

Australia's Industry Growth Programme offers tailored advisory services alongside the opportunity to apply for grants for early-stage commercialisation and scaling. The programme offers the equivalent of USD 30 000 to USD 3 million to businesses in priority areas of the National Reconstruction Fund, including renewables and other low-emissions technologies.

Other examples of centralised portals include the UKRI Funding Finder in the United Kingdom, Grants.gov in the United States and Enterprise Singapore's grants portal.

Grants for scaling up

Governments can 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 when they can be claimed before construction begins.

Selected new or updated grants for scaling up, 2025

Austria

The Transforming Industry programme, launched in 2025, with a first call of USD 325 million, will provide USD 3.2 billion through 2030 to support industrial projects achieving at least a 60% reduction in emissions, or annual savings of more than 5 000 tonnes of CO_2, with a focus on electrification, hydrogen and CCUS, through grants for investment and operating costs.

Canada

Ucore, a mining and processing company, received conditional approval for up to USD 25 million to build a first-of-its-kind commercial facility to refine rare earth elements used in nuclear magnets.

European Union

The USD 3.1 billion 2025 Net-Zero Technologies call of the EU Innovation Fund targets decarbonisation projects that demonstrate highly innovative, near-market technologies with strong potential for substantial emissions reductions. The 2025 call is 20% larger than in 2024, removes the ring-fenced budget for battery manufacturing, and increases funding for cleantech manufacturing and pilot projects by nearly 50%.

Spain

The Spanish government granted approximately USD 880 million for energy storage projects, pre-selecting 126 projects, including thermal storage for the electrification of industrial heat, battery storage with grid-forming capabilities and other storage systems.

Equity finance, including venture capital

Innovators aiming to develop new products within a start-up typically raise much of the capital for prototypes, pilots and demonstrations as equity. The availability and cost of venture capital (VC) varies between regions and has traditionally been much more accessible to start-ups in the United States. In countries with less-developed VC systems, governments sometimes inject public capital as a means of stimulating private co-investment. Sometimes this is via public VC funds and sometimes by investing in private venture funds. Public VC funds accounted for 5% of energy VC funding in 2025 (Chapter 2).

Equity is a "dilutive" type of finance, which means that companies must hand over a stake in return for capital.[9] Compared with grants, this reduces founders' future returns and some strategic control, but also brings commercial discipline and the valuable experience of the investor team.

Selected new or updated equity instruments, 2025

Brazil

Brazil is establishing a 12-year private equity fund to take minority stakes in technology-based start-ups in areas such as renewable power, energy storage, electric mobility, sustainable fuels and industrial decarbonisation from 2026. Eligible companies must have validated solutions and early recurring revenue. The fund is expected to total around USD 75 million, with contributions from Petrobras, a state-owned oil company, the national development bank and FINEP, the main R&D funding agency. A fund manager with investment autonomy is being competitively selected.

The national development bank, BNDES, issued its largest ever call, budgeting up to USD 0.9 billion. By early 2026, up to USD 0.7 billion will be allocated to stakes in up to five private equity funds and up to USD 0.2 billion to up to two credit funds focused on energy transition, sustainable agriculture and forest conservation. Awardees have been selected from 45 proposals.

China

In March 2025, China announced a National Venture Capital Guidance Fund to support high-tech sectors such as AI, quantum technologies and energy, expected to mobilise the equivalent of USD 140 billion over 20 years. In May 2025, several ministries and institutions issued measures to build on this fund and take further steps towards a finance system that fosters innovation. In December 2025, China launched three regional VC funds under this framework, each with capital of around USD 7 billion, covering the Beijing-Tianjin-Hebei cluster, the Yangtze River Delta, and the Guangdong-Hong Kong-Macau Greater Bay Area.

[9] Another type of equity finance of relevance to first-of-a-kind commercial projects is project equity. This gives the investor a stake in the project, but it ringfences the other assets of the promoters from claims in the case that the project underperforms. However, it is rarely used for pre-commercial energy projects due to a level of technology risk that investors, such as infrastructure funds, do not typically accept.

In May 2025, Sinopec, a state-owned oil company, launched a roughly USD 700 million hydrogen-focused venture fund to invest across the value chain. It has attracted private co-investors.

Finland

Tesi, a state-owned investment firm, took on an expanded industrial policy mandate, with USD 1.9 billion in investment capacity for 2025-2029, to be split between VC funds, private equity funds and direct investments. The new mandate emphasises scaling up innovative Finnish companies via industrial clean energy projects. In July 2025, Tesi invested in Norsk e-Fuel, a Norwegian developer of synthetic aviation fuel technology.

Malaysia

A National Energy Transition Facility was introduced in 2025 under the National Energy Transition Roadmap. Managed by state-owned Malaysia Debt Ventures with around USD 25 million, it will support 20-30 technology-based companies with redeemable or convertible preference shares, convertible debt, rebates and credit enhancement.[10]

United Kingdom

The UK government announced approximately USD 25 million to seed a private investment fund targeting fusion energy.

Some equity instruments that were already in place in 2024 made notable investments in 2025 or reoriented their energy focus areas. In addition, Brazil held a third auction of a currency-hedging programme that is designed to mobilise USD 340-690 million in equity investment in Brazilian start-ups focused on energy (including biogas, biofuels, synthetic liquid fuels, EVs and battery materials). Supported by the Inter-American Development Bank, this initiative reduces overseas investors' exposure to currency volatility by guaranteeing them 50% of their expected financial return if the Brazilian real depreciates.

[10] Redeemable or convertible shares are a type of preferred equity that offers investors higher chances of repayment than ordinary shares, but usually comes with no voting rights. Redemption rights allow investors to require the company to buy back the shares at an agreed price under predefined conditions. Convertible preference shares offer a fixed rate of return and can be converted into an agreed number of ordinary shares or cash. Convertible debt is a loan instrument that may be repaid by conversion into equity under predefined conditions at a later financing round, allowing early-stage support while deferring initial equity dilution. Rebates reimburse a share of eligible costs after expenditure. Credit enhancement instruments, such as guarantees, reduce the risk of non-repayment, thereby improving the creditworthiness of borrowers (start-ups) and making it easier for them to access finance while lowering their financing costs.

Selected new equity investments by existing initiatives into energy companies and funds, 2025

Canada

Canada Growth Fund, active since 2023, provided a second equity investment to Eavor's closed-loop geothermal technology (USD 100 million), following an initial investment in 2023, and to dcbel's bidirectional EV-charger (USD 40 million), and an equity-like royalty plus offtake for Rio Tinto's scandium plant (USD 17 million), a rare earth element.

European Union

In August 2025, the EIB launched the TechEU Programme to unify and streamline its technology financing tools, bringing together direct equity co-investments and investments in funds under a single platform, with energy as a priority. EIB direct equity co-investments in energy mainly target the deployment of mature technologies. In 2024, together with the European Investment Fund, the EIB launched the USD 215 million Cleantech Co-Investment Facility, which is open for proposals but has not yet allocated funding.

The European Tech Champions Initiative is a USD 4.2 billion fund that is capitalised by the EIB and invests via other, third party, funds. It has so far backed 12 growth equity funds. In December 2025, a second phase was announced, adding USD 1.3 billion to support both large and mid-sized funds.

The European Innovation Council's STEP Scale Up scheme had a budget equivalent to USD 325 million in 2025. It backs start-ups with USD 11-32 million of equity and has energy as a priority focus. Its first investment in November 2025 backed Zadient Technologies, a French start-up developing semiconductors for EVs and renewables. The Council also had a budget of USD 250 million for smaller equity investments made alongside grants. CorPower, a Swedish ocean energy start-up, and Copenhagen Atomics, a Danish nuclear start-up, each received a USD 2.7 million grant, alongside a pre-commitment of up to USD 16 million in equity.

Germany

The DeepTech & Climate Funds provided equity to Proxima Fusion for its stellarator-based fusion plant, to Ferroelectric Memory Company for low-energy chip technology and to Genomines for plant-based metal extraction from soil (e.g. for nickel). In 2026, the fund will be integrated within High-Tech Gründerfonds to consolidate financing for technology companies within a unique VC platform.

NATO and Norway

The NATO Innovation Fund, established in 2022, made its first energy-related investment in 2025. It led a USD 13 million seed round (alongside Norway's sovereign investment fund) for Kongsberg Ferrotech, a Norwegian start-up developing robotic solutions for offshore infrastructure. The fund, backed by 24 NATO countries, facilitates access to nearly 90 NATO-affiliated test centres and over 6 000 scientists.

Loans, including venture debt

Provision of debt by governments to projects or companies can have several 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. Public debt can also provide a strong signal that the project has passed government due diligence, thereby lowering perceived risks for co-investors.

Debt is a "non-dilutive" type of finance, which means that companies do not have to hand over part of their value in return for capital. It is usually cheaper than equity financing. Public debt support is most often directed towards companies approaching commercialisation and scale-up, but some instruments – such as venture debt – may target earlier stages of development. Governments typically deploy debt through public financial institutions, including sovereign wealth funds, public pension funds or state-owned banks.

Selected loans and loan guarantees relevant for energy technology innovation, 2025

European Union

The TechEU Programme (see above) encompasses venture debt,[11] loan and guarantee instruments. In 2025, the EIB provided venture debt to Meva Energy (around USD 45 million) for biomass-waste gasification, to Trailer Dynamics (USD 25 million) to develop an electric trailer with its own battery and motor that reduces fuel use when paired with a diesel truck or extends driving range with an electric truck, and to INERATEC (USD 45 million) to scale up synthetic fuel production.

In 2025, EIB project loans included USD 270 million to Vulcan Energy for Europe's first geothermal brine direct lithium extraction, USD 280 million to Stockholm Exergi for Sweden's first large-scale bioenergy plant with CCUS, and USD 270 million to Nexans to expand cable production and copper recycling. The EIB also has a programme of R&D loans for well-capitalised firms, which in 2025 extended USD 215 million to Prysmian for R&D on high-performance, lower-emission cables, USD 540 million to Sandvik for R&D on mining technology, USD 540 million to TRATON for fuel-efficient trucks and USD 85 million to CAF to support innovation in the rail sector.

EIB counter-guarantees demonstrate how they can help firms attract private capital, including for innovation-related activities. A USD 55 million counter-guarantee provided to support Navantia Seanergies' wind manufacturing, including innovative floating foundations, unlocked over USD 110 million in private bank guarantees, enabling the company to receive advance payments and issue performance guarantees without tying up large amounts of funds in escrow accounts. EIB and the private bank Société Générale signed a memorandum under which EIB will provide USD 270 million in guarantees, enabling the bank to offer working-capital facilities to cleantech start-ups so they can issue advance-payment and performance guarantees.

Japan

The Zero-Emission Accelerating Ship Finance Program, launched in 2022 by the Development Bank of Japan and ClassNK to offer preferential low-interest loans (and potentially equity) for low-emissions vessels, was used for a coastal ship the first time in 2025 – a hydrogen-ready oil tanker.

[11] Venture debt is a form of non-dilutive financing for start-ups, typically carrying higher interest rates than conventional loans to reflect greater risk, while avoiding the equity dilution associated with VC.

Lithuania

In March 2025, a new loan facility for energy storage projects with a budget of up to USD 110 million was launched. By May 2025, USD 60 million had been allocated to enhance grid stability amidst Lithuania's synchronisation with continental Europe. The loans were provided through the state-owned bank ILTE's "Billion for Business" instrument, which supports decarbonisation projects.

Spain

In July 2025, a call was launched to provide the equivalent of USD 195 million in loans (at a 2.7% rate, with a 10-year amortisation and a 3-year grace period) and USD 110 million in grants for manufacturing EV batteries and components, or producing or recovering related raw materials.

United States

The Office of Energy Dominance Financing agreed a USD 1.3 billion loan to ENTEK for the first US wet-process lithium-ion battery separator facility. Other loans in 2025 were for mature technologies in nuclear fission and electricity grids.

Multi-instrument funds

Some investment funds created by governments to support innovation can be used in multiple ways – such as grants, debt or equity – without specifying the shares upfront. In most cases, they are not wholly dedicated to energy innovation.

Selected new multi-instrument funds, 2025

Australia

Australia's Future Made in Australia Fund (USD 945 million) will support pre-commercial innovation, demonstration, and deployment on three areas: green metals; clean energy technology manufacturing to address critical supply chain challenges; and low-emissions liquid fuels, including sustainable aviation fuels. Funding will be provided as grants but may include recoupable grants.[12]

Germany

Germany's Special Fund for Infrastructure and Climate Neutrality has a broad range of priorities, including energy infrastructure and R&D. Around USD 110 billion, 20% of the total, is allocated to clean energy supply, energy efficiency, renewable heating in buildings, sustainable transport, industrial transformation, hydrogen and nature-based solutions.

European Union

In October 2025, the Scaleup Europe Fund was announced as part of the EU Startup and Scaleup Strategy. The concept of the multi-billion-euro fund is to pool public and private resources for scale-up of promising EU companies in strategic science-intensive sectors, including energy.

[12] A recoupable grant provides upfront grant funding that is repayable only if predefined success milestones are achieved, sitting between a traditional (non-repayable) grant and a loan.

India

India's Research, Development and Innovation Fund (around USD 11 billion) supports a wide range of technologies with a strong focus on energy security and the energy transition. It can finance project costs for R&D projects at TRL 4 or higher, providing long-term low- or zero-interest loans and equity investments, or contribute to other funds.

Korea

The Science and Technology Innovation Fund (around USD 685 million) supports the commercialisation of national R&D results and the growth of deep tech start-ups across 12 national strategic technologies, including secondary batteries, next-generation nuclear power, hydrogen, aerospace and the marine sector. It invests in smaller funds that take equity in domestic innovators.

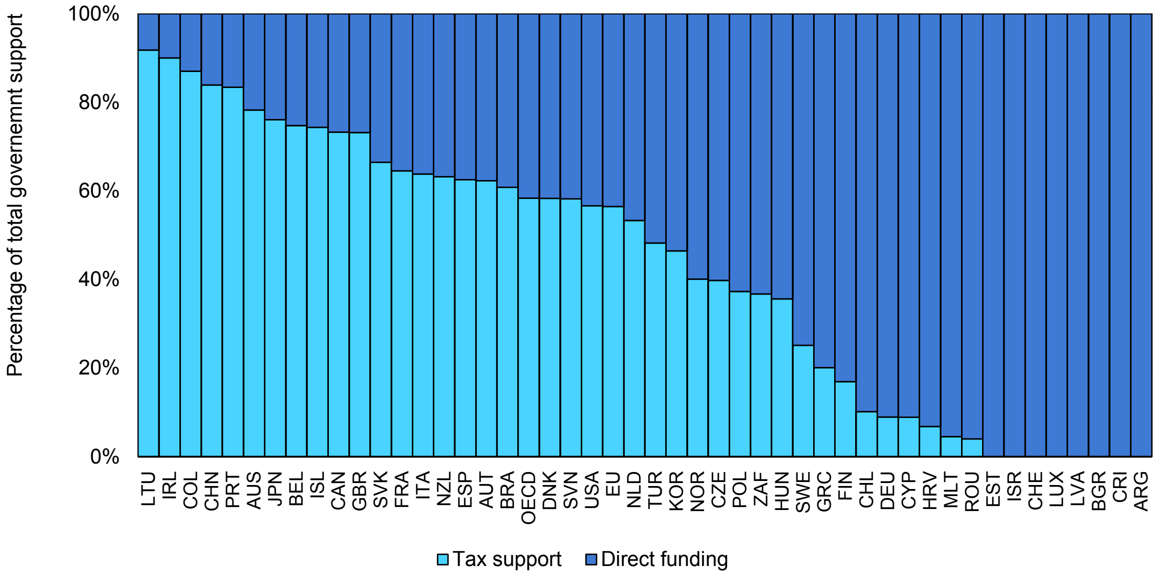
Tax incentives

Governments can lower tax liabilities for firms performing R&D, investing in first-of-a-kind projects or the earliest stages of deployment, or generating output from such projects.

R&D tax incentives represent the most significant form of government support for business innovation, but they are not directed towards any specific innovation area, such as the energy sector. They are relatively easy for governments to implement with a lower administrative burden. In general, beneficiaries must be earning taxable income, limiting accessibility for early-stage start-ups unless incentives are refundable or deferred.

Among advanced economies, tax incentives represent over half of total government support for business R&D, and more than 80% in some countries. However, no country systematically collects or publishes statistics on tax credits claimed by companies to be used for energy-related R&D.

Tax support as a share of total government support for business R&D, 2023

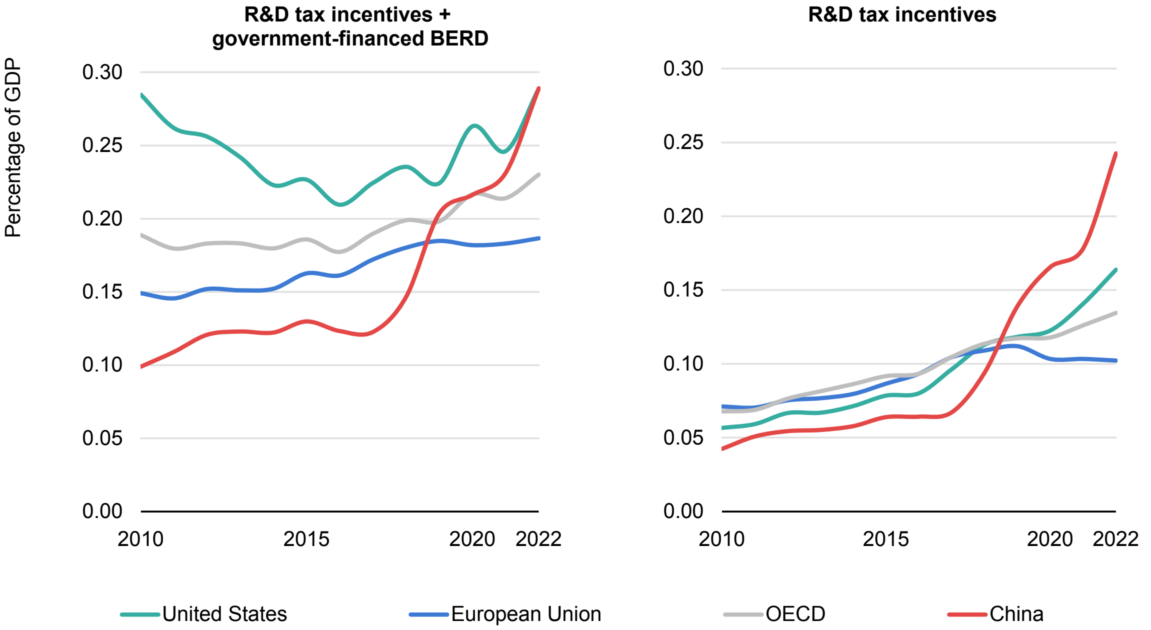


Notes: The three-letter codes used on the x-axis are ISO 3166-1 alpha-3 codes for countries. OECD = average across Members of the Organisation for Economic Co-operation and Development. Total government support includes tax incentives and grants.
Source: OECD (2025), OECD R&D Tax Incentives Database, (accessed October 2025).

The scale of R&D tax incentives varies across regions and over time.[13] Over the past decade, government tax incentives for business R&D have increased significantly in all regions, both in absolute terms and as a share of total public support for R&D. While these incentives are not specific to energy-related R&D, they provide a useful indication of the broader policy environment for private sector R&D. By 2022, China had nearly tripled the level of support it provides to business R&D compared with 2010, with particularly rapid growth since 2018, reaching 0.24% of GDP in R&D tax incentives in 2022. This compares with 0.16% in the United States and 0.10% in the European Union. Overall government support for business R&D in the European Union remains around one-third lower than in the United States and China, with an ever-wider gap in support delivered through R&D tax incentives.

[13] The design of these incentives also varies. Some reduce tax liabilities based on the amount firms spend on eligible R&D; some lower taxes on income from sales; and some reduce taxes on internally generated R&D assets. In general, the latter category is better suited to smaller firms that lack a steady revenue stream from sales.

Government support for business R&D, 2010-2022



Notes: BERD = Business Enterprise Research and Development. Data for government financed BERD in the European Union for 2022 are not available, so the value was estimated using linear interpolation between 2021 and 2023.
Source: OECD (2025), OECD R&D Tax Incentives Database, (accessed November 2025).

Selected new or updated tax incentives, 2025

Australia

Australia plans to introduce a refundable tax offset of 10% for eligible entities on expenditure related to processing or refining any of 31 listed critical minerals. The offset will be available for up to 10 years for production between 2027 and 2040. Expenditure on intellectual property can be included in the tax offset calculation up to 10% of the company's total expenditure.

In 2025, a temporary USD 1.25 per kilogramme tax incentive was established for hydrogen production from renewable electricity. It will be available to projects taking final investment decisions by 2030, with production between 2027 and 2040.

Canada

Canada's 2025 federal budget expanded the scope of several tax credits, extending the Clean Technology Investment Tax Credit to the less mature technologies of waste biomass and SMRs, broadening the Clean Technology Manufacturing credit to innovative mining and extraction, processing and recycling of co-product critical minerals, extending the Clean Hydrogen Investment Tax Credit to methane pyrolysis, and prolonging the full value of the CCUS tax credit by 5 years through 2035.

Chinese Taipei

Chinese Taipei amended its Industrial Innovation Statute, expanding the investment tax credit to cover energy conservation and carbon-reduction projects, alongside digital technologies. Claimants receive a credit of 5% of investments up to USD 55 million (compared with USD 30 million previously) in the current year, or 3% carried forward up to 3 years.

European Union

The European Commission recommended accelerated depreciation[14] (up to immediate expensing) and targeted tax credits to its member states in support of the Clean Industrial Deal.

Finland

Finland introduced a tax credit for large clean transition investments, including renewable energy, energy storage, industrial decarbonisation, energy efficiency, and the production of strategic equipment, components and raw materials. This provides a 20% tax credit on eligible costs, capped at around USD 160 million per company.

Innovation inducement prizes

Innovation inducement prizes are future rewards offered to motivate individuals or organisations to solve a specific problem or achieve a particular innovation goal. By offering financial incentives and public recognition, they encourage innovators to take risks they might otherwise avoid. Prizes can generate a variety of solutions, including approaches that would not have been funded under traditional R&D funding models. Some schemes provide complementary support such as mentoring, access to testing facilities, or the provision of relevant data, but participants carry the upfront R&D risk, rather than the sponsor. While governments use this policy tool, it has traditionally been used more by private sponsors such as philanthropic organisations.

Selected new or updated innovation inducement prizes, 2025

Germany

The Long-Duration Energy Storage Challenge concluded in June 2025, with the jury selecting all four finalist teams as winners. Teams received up to USD 1.1 million each in the first stage and USD 3.2 million in the final stage, plus advisory services. The winners developed ideas for a new solid oxide fuel cell, iron-air battery and membrane-less redox-flow battery.

[14] Accelerated depreciation allows firms to deduct a larger share of an asset's cost in the early years of its lifetime, reducing taxable income immediately. Deferring tax payments to later years increases the present value of tax relief, since taxes paid later have a lower present value than those paid today.

India

The Innovative Projects Start-up Grand Challenge was launched with a budget of approximately USD 265 000 for rooftop solar and distributed renewable energy technologies. The first prize is equivalent to USD 115 000 and selected teams receive support from a public R&D institute.

United States

The Feeder of the Future Prize is a USD 100 000 single-phase competition for innovative electricity grid designs, focusing on power distribution feeders, awarding up to 10 winners with USD 8 000 each and up to 8 runners-up with USD 2 500 each.

United Kingdom

The government-backed Manchester Prize completed its first round in 2025, with Polaron, a start-up, winning the USD 1.3 million prize for AI to advance the development of new materials for batteries. Round Two, focused on AI applications for a net zero energy system, announced ten finalist teams, each receiving USD 130 000 in seed funding and up to USD 80 000 in computing and non-financial support to further develop their solutions, with the winner to be selected in 2026.

Demand-creation measures

A wide range of government policies support consumer demand for energy technologies, from fossil fuels to energy-efficient equipment. For most of these policies, innovation is not a primary objective, even if market demand can stimulate innovation to outcompete less innovative products. The policies listed below are those that explicitly target energy technology innovation.

Public procurement

Governments can prioritise the purchase of goods and services that use emerging technologies. This can take the form of more stringent criteria for public procurement in terms of environmental performance, or direct purchases to create a market that did not previously exist at scale, such as for high-quality carbon dioxide removal (CDR) credits or near-zero emissions materials. Public procurement has been estimated to represent 12.7% of GDP in advanced economies and account for 30% of government expenditures. It is especially important in sectors such as construction and transport: public procurement is estimated to account for around one-third of cement production and one-quarter of steel production in some countries. Procurement requirements could create markets for technologies on the cusp of commercialisation. However, standards and criteria are often decentralised within countries, posing co-ordination challenges.

Selected new or updated public procurement schemes, 2025

Canada

The Low Carbon Fuel Procurement Program has a total budget of USD 95 million over 8 years for the purchase of low-emissions liquid fuels for the federal air and marine fleet. In 2024, it was expanded to include CDR, and a request for information about available credits was issued in 2025. The government has committed to purchase at least USD 7 million in CDR services by 2030.

The Policy on Green Procurement was updated in 2025 to require whole-building lifecycle assessments of material use, to include other materials with low-emissions intensity, including steel and concrete.

European Union

Under its Clean Industrial Deal, the European Commission announced plans to review its public procurement framework in 2026 to promote sustainability, resilience and European preference in strategic sectors. The upcoming Industrial Accelerator Act may introduce non-price criteria and a voluntary carbon-intensity label for industrial products, starting with steel.

Germany

The 2026 federal budget allocated USD 12.4 million for the purchase of CDR certificates, as part of a broader budget allocation focused on CDR, including USD 105 million in addition for CDR projects.

United States

The Boston Housing Authority piloted compact window heat pumps to replace electric-resistance heating systems in a public housing complex, using units supplied by Gradient, a start-up.

Publicly backed offtake contracts and revenue guarantees

Offtake contracts are firm agreements from customers to buy future output, and they can significantly reduce the 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 are lowered. Aside from public procurement, governments can guarantee offtake revenues by agreeing fixed payments for output or performance, such as CO_2 reductions. By setting criteria that mature technologies cannot achieve, it acts as top-up revenue for innovative technologies that improves their competitiveness. Contracts for difference (CfDs) are a type of agreement through which producers are guaranteed a fixed price, but the government is only responsible for incremental costs above a market benchmark, with consumers paying the rest. Such contracts are typically awarded via auctions to the lowest-cost bidder, but some governments hold separate auctions for less mature technologies.

Selected new or updated government-backed industrial incentives, 2025

Australia

Under the Cleaner Fuels Program, a budget equivalent to USD 700 million has been earmarked for grants to domestic low-emissions liquid fuel producers over 10 years, paid based on production volumes.

The second round of the Hydrogen Headstart scheme was launched, providing a further USD 1.3 billion in payments based on production volumes over 10 years. This round targets high-priority uses, such as metals (iron and alumina), ammonia and long-haul transport.

Denmark

In 2025, the Danish Energy Agency launched the carbon capture and storage (CCS) Fund tender, with a budget of USD 4.2 billion for 15-year contracts for CO_2 capture, transport and permanent storage. Support is source-neutral, with no earmarking by CO_2 origin, which can be fossil, biogenic or atmospheric CO_2.

European Union

Successful applicants to the third auction of the Innovation Fund European Hydrogen Bank can receive a fixed payment for up to 10 years to top up expected private sales revenues. It is capped at the equivalent of USD 4.3/kg H_2 and a total budget of around USD 1.4 billion is available. Producers of hydrogen or hydrogen-based fuels are eligible and 23% of the budget is earmarked for sales to the maritime and aviation sectors. Under the auction-as-a-service scheme, **Germany** has allocated USD 1.4 billion, and **Spain** USD 450 million, to support eligible projects that meet all criteria but do not secure funding, reducing administrative costs associated with new calls.

Also under the Innovation Fund, the Industrial Heat auction was the first EU-wide tender for industrial process heat projects and served as a pilot for the Industrial Decarbonisation Bank. Successful applicants will receive 5 years of payments per tonnes of avoided direct CO_2 emissions. The budget is equivalent to USD 1.1 billion, and the scope includes heat pumps, electric boilers, plasma torches, resistance or induction heating, solar thermal and geothermal. Member states can top up funding through the auction-as-a-service scheme.

The eSAF Early Movers' Coalition was launched in 2025, bringing together Austria, Finland, France, Germany, Luxembourg, the Netherlands, Portugal and Spain to mobilise at least USD 540 million. It will use double-sided auctions: long-term contracts to sustainable aviation fuel (SAF) producers, providing revenue certainty, and short-term contracts to off-takers, with the first auction planned for 2026.

France

The European Union approved a USD 12 billion programme to support floating offshore wind farms with 20-year CfDs.

Germany

The 2026 Climate Protection Contracts round will include CCUS for the first time. It has a budget equivalent to USD 5.5 billion for 15-year CfDs in sectors such as steel, cement, chemicals and glass. Payments are sized to close the gap between cost premiums and CO_2 prices.

India

State-owned Solar Energy Corporation (SECI) completed its first renewable ammonia procurement tender, awarding 10-year, fixed-price delivery contracts and production subsidies for the first 3 years. SECI acts as an intermediary, aggregating demand and selling the ammonia to fertiliser producers.

Italy

Through the Electricity Storage Capacity Procurement Mechanism (MACSE), Terna, the Italian transmission system operator (TSO), auctioned 15-year long-duration energy storage contracts for the first time, awarding 10 GWh in total. While pre-commercial technologies were eligible, on this occasion the winners were lithium-ion batteries.

Netherlands

The SDE++ scheme reopened in 2025 with an allocated budget of USD 8.6 billion. Projects compete based on CO_2 abatement costs and receive a payment based on output, intended to bridge the gap between production cost and market value for up to 15 years. Five energy technology categories allow less mature technologies to compete against one another.

Japan

The first four awards were certified for 15 years under Japan's USD 20 billion hydrogen CfD, requiring at least 10 years of operation post-subsidy. One project will supply steel production, while the other three will supply ammonia, including two awards jointly developing an ammonia production project in the United States.

Singapore

In 2025, the Civil Aviation Authority of Singapore established the Singapore Sustainable Aviation Fuel Company (SAFCo) to centrally procure SAF using a levy-funded SAF fund. SAFCo will supply SAF to meet Singapore's 1% blending target for departing flights in 2026, rising over time, while also aggregating demand to generate economies of scale in procurement.

United Kingdom

The Long Duration Electricity Storage cap and floor scheme is open to projects offering at least 8 hours of storage. It has a category for less mature technologies – liquid air, compressed air and flow batteries – at 50 MW per project (compared with 100 MW for others). Above the cap, market revenue is redistributed to consumers.

The next round of contract-for-difference auctions for electricity generation will provide 20-year contracts (instead of 15) for fixed-bottom offshore wind, floating offshore wind, onshore wind and solar technologies, and will extend phasing[15] to the more innovative floating offshore wind projects, which will also have 10% higher price ceiling. The round includes different pots with ring-fenced budgets, including one each for offshore wind and floating offshore wind, one for established technologies and one for emerging technologies, including wave and tidal stream.

[15] Phasing allows projects to be built in several stages to lower project delivery risks.

Access to research infrastructure

Governments play a vital role in supporting innovation by providing access to state-of-the-art research facilities, testing labs and pilot plants, as well as high-performance computing systems. This gives smaller research institutes and SMEs the opportunity to develop, validate and scale technologies that would otherwise be prohibitively expensive to undertake, while ensuring efficient use of publicly funded research infrastructure. In some cases, this support extends beyond physical assets; for example, the United States is exploring access to curated scientific datasets through its Genesis Mission.

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

Canada

In 2025, Canadian Nuclear Laboratories re-launched its SMR Siting Programme as the Clean Energy Siting Programme, expanding its scope to include fusion, hydrogen and battery storage.

China

The 2025 Burning Plasma Programme opens several national fusion energy research platforms to scientists worldwide, including the under-construction BEST Tokamak.

The 2025 edition of the Service Manual for Opening Central Enterprises' Pilot Verification Platforms to the Public lists 134 facilities at state-owned enterprises – including for CCUS, low-emissions fuels and energy efficiency – that are open for external researchers to access.

Denmark

The Roadmap of Research Infrastructure 2025-2028 identifies research infrastructure projects of strategic importance for Danish and European research. It outlines principles for such facilities, including broad accessibility through common access points and consortium-based operation to ensure high utilisation of expensive equipment. Two energy projects were funded in 2025: the Nuclear Salt Loop Facility for molten salt fission R&D and the Danish Fusion Infrastructure.

Germany

With the first site opening in September 2025, a new Innovation and Technology Centre for Hydrogen will support companies in the road, maritime and aviation sectors with specialised testing and certification not yet available on the market, with federal funding of up to USD 310 million for the four locations.

Japan

In 2025, Helical Fusion, a fusion energy start-up, was granted permission under the Venture Support Programme to incorporate and use National Institutes of Natural Sciences (NINS) intellectual property. Such "NINS Ventures" have ongoing access to testing and experimental infrastructure.

Korea

In 2025, a national research institute established a centre to validate CO_2 capture and utilisation technologies. The USD 15 million test centre will first be used by GS Caltext, a chemical company.

Saudi Arabia

The National Open-Access Portal for Research Infrastructure provides a single-entry point for innovators to access more than 1 000 research laboratories as well as equipment and expertise, including in energy. In parallel, under its Reactivation and Rebuilding of Existing Labs initiative, Saudi Arabia allocated around USD 85 million to upgrade existing laboratory facilities.

United States

In November 2025, the Genesis Mission was launched by executive order to integrate R&D across high-performance computing, secure AI environments, quantum technologies and federal scientific datasets. From 2026, it will be supported by national energy laboratories and major digital companies to provide public and private researchers with computational and data resources in areas including nuclear fission and fusion, grids, critical materials and advanced manufacturing.

Regulatory sandboxes and living labs

Regulatory sandboxes provide regulatory exemptions or freedoms to facilitate the testing of new products and services in a safe way for a temporary period. The sandbox approach means that test projects are not exposed to the full costs and risks of regulatory compliance, but there are safeguards to protect consumers and the energy market. Navigating international, national and local regulations requires levels of time and resources that are often only available to large companies, and regulatory sandboxes can reduce complexity for smaller companies and start-ups with fewer resources. Regulatory frameworks that do not foresee certain applications of technologies often need stress-testing before the they can be updated. For technologies for which testing requires engagement with consumers or the wider public, centrally co-ordinated "living labs" of real-world project participants can be made available.

Selected updates on regulatory sandboxes for energy technologies, 2025

Australia

The Australian Energy Regulator introduced a policy-led sandbox approach, complementing its existing demand-led Energy Innovation Toolkit, which serves as a one-stop shop for companies to access multiple regulatory bodies. This new approach enables larger-scale trials. The first trial waiver was granted for the operation of 130 MWh of battery assets.

European Union

Since 2024, the European Union has required its members to establish regulatory sandboxes. In 2025, a call was launched to fund an NZIA Regulatory Sandbox Exchange Forum, including work on comparative analyses of national frameworks for sandboxes relevant to net zero technologies.

Italy

The Energy Regulatory Authority extended its scheme for experimental smart residential EV charging through 2027, allowing participants to use more power during off-peak periods.

Korea

Korea approved dozens of new regulatory sandbox projects targeting innovation in mobility and hydrogen, including a wireless-charging pilot for self-driving EVs and a hydrogen-powered unmanned underwater vehicle for the Agency for Defence Development.

Moldova

The Energy Sandbox Mechanism became operational and is open to applications, with priority areas including electromobility, flexibility and grid balancing, smart grids and biofuel production.

Singapore

The Energy Market Authority launched a 2-year Virtual Power Plant Regulatory Sandbox to assess how aggregated distributed energy resources can provide energy and ancillary services to the grid. Participants include technology start-ups, universities and other industry partners.

United States

The Connecticut Public Utilities Regulatory Authority's Innovative Energy Solutions Program functions as a regulatory sandbox. In 2025, its annual call was on "Smart Energy Communities".

Knowledge management

Effective national energy innovation relies on well-structured knowledge management platforms that create synergies among researchers, investors, policy makers and technology users. The connectedness of information acts as a critical infrastructure for the innovation ecosystem, enabling collaboration, reducing duplication and accelerating technological development. Like physical infrastructure, this knowledge infrastructure can be a "public good", giving governments a central role in its promotion.

Co-operation on energy technology has been a core pillar of the IEA's work since its establishment in 1974. Since 1975, the IEA's Technology Collaboration Programme (TCP) has provided governments, industry and research institutions with a long-standing framework for knowledge-sharing on innovation efforts, often supported by public funding. With nearly 40 collaborative initiatives currently active, the TCP is one of the energy sector's most enduring knowledge-management mechanisms. Countries are also launching new, targeted co-operation initiatives in strategically relevant areas, seeking to align efforts more effectively and accelerate progress beyond what could be achieved acting alone.

Selected new or updated policies for enhanced knowledge management, 2025

Canada

The e-Auto Challenge programme provides funding and resources for experts across the light-duty vehicle value chain – from industry, academic, non-profit and public sectors – to collaborate.

Colombia

The Ministry of Mines and Energy created a Graphene Innovation Hub to bring together scientific, industrial and governmental expertise, and foster new nanomaterial-based industries.

European Union

In 2025, the European Innovation Council Trusted Investor Network (established in 2024) expanded from 71 to 111 members who collectively manage over USD 360 billion in assets. It convenes institutional investors committed to investing in science-led start-ups alongside EU funds.

An Innovation Centre for Industrial Transformation and Emissions was launched in 2024 to serve as a central EU hub for evaluating and promoting advanced low-carbon industrial technologies.

Spain

Launched in 2025, INNTERCONECTA STEP Regional Consortia requires recipient companies to form consortia of 2-6 firms for collaborative R&D (TRL 3-6) in Spanish regions with lower industrial development. The scope covers digital, clean and efficient technologies and biotechnology.

Norway

New Environment-Friendly Energy Research Centres were launched in 2025 for zero-emissions metals, integrated energy planning, resilient electricity grids, maritime energy transition, large-scale CCUS and advanced batteries. Each centre gets up to 8 years of funding for collaborative R&D.

In 2025, a single contact point for international collaboration (CCUS Innovation) was created by merging CCUS Norway and CCS Innovation.

United States

The Geothermal Power Accelerator is a network of 13 states that brings together states, federal agencies and geothermal developers to unlock investments through strategy and policy discussions, cross-government co-ordination and information exchange.

Recognition awards

Recognition awards formally acknowledge technological excellence, helping to raise its legitimacy, value and visibility. Such recognition can also act as a government mark of quality that helps innovators attract additional resources or partnerships and disseminate knowledge. Depending on the design, awards can facilitate the sharing of knowledge and recognise work at different stages of maturity.

Selected new or updated recognition awards, 2025

European Union

The 2025 EUSEW Awards Ceremony recognised Dutch start-up Aquabattery for its acid-base flow battery. Additional prizes were awarded for Local Energy Action and Women in Energy.

The Clean Hydrogen Partnership Awards recognises leading projects participating in its initiatives. In 2025, winners included HyP3D (3D printing to manufacture solid oxide electrolysis cells), HELIOS (retrofittable 100% hydrogen gas turbine) and FLEX4H2 (fuel-flexible combustor).

Germany

The German Energy Agency's Energy Efficiency Awards have been organised since 2007. Winners in 2025 included Pöppelmann (more sustainable plastic production process), KIS Antriebstechnik (AI-supported energy management system), Stadt.Energie.Speicher and denkmalstadt (district energy with river water heat pumps) and tesa SE (adhesive production using hydrogen).

Ghana

The Innovate Ghana Innovation Challenge 2025, organised by Innovate Ghana, Innovate Labs and StArfrica, targets Ghana-based sustainable energy innovations, offering finalists mentoring, technical support, and up to USD 10 750, funded in part by Germany.

International collaboration

International collaboration is essential to accelerate energy technology development, reduce risks and benefit from the insights and perspectives of a wider range of research contexts. By pooling expertise, leveraging comparative advantages, and sharing knowledge, countries can advance research and innovation more efficiently than they can in isolation. This principle underpins the IEA's Technology Collaboration Programmes, which celebrated their 50th anniversary in 2025. International energy innovation co-operation examples can be grouped by their objectives:

Share risks and pool resources behind common priorities. Large-scale energy projects are often too expensive and risky for any single country to pursue alone. Collaborative efforts enable countries to share costs, reduce risks, and co-ordinate innovation efforts. This allows multiple countries to participate in emerging technologies without facing prohibitive financial or technical risks.

- In 2025, several collaborative nuclear fusion projects achieved significant milestones, including ITER, Wendelstein 7-X and the Chinese International Science Program on Fusion Burning Plasma. Each reflects the collective expertise and co-operation of numerous international partners.
- New Zealand and Iceland signed a co-operation agreement on superhot and supercritical geothermal systems.

- As in previous years, the EU Clean Energy Transition Partnership opened its USD 86 million annual multi-source transnational call with funding from 40 national/regional funding organisations from 30 countries in 2025.

Develop common standards and avoid fragmentation. Common standards, including those developed by international (International Organization for Standardization [ISO], International Electrotechnical Commission [IEC]), regional (European Committee for Standardization [CEN], European Electrotechnical Committee for Standardization [CENELEC]) and national standards bodies, can support energy innovation by providing replicable methods and helping ensure that technologies and services are developed, manufactured and deployed in ways that are safe, cost-effective and environmentally sustainable. Standards can also lower market entry barriers for new and foreign entrants and enable interoperability across systems and markets. At the earliest stages of deployment, access to international markets is important, yet standards may be inconsistent or non-existent. International co-operation can help harmonise standards or, at least, make them interoperable, avoiding market fragmentation. Notable developments in 2025 include:

- The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an intergovernmental initiative of 27 countries and the European Commission. It has developed a methodology for calculating lifecycle GHG emissions from hydrogen production, which has informed ISO/TS 19870 (technical specification) and is now being converted into a full international standard based on the IPHE approach. In May 2025, China proposed new industry standards for low-emissions hydrogen, aligning with other international benchmarks, particularly those in the European Union.
- The IEA TCPs provide a framework for pre-normative research, serving as platforms for joint international work that supports pre-standardisation activities. An example from 2025 is ongoing work under the Photovoltaic Power Systems TCP on building-integrated photovoltaics (BIPV), which aims to help harmonise standards by bridging gaps between BIPV and construction regulations, in co-ordination with ISO, IEC and CENELEC.
- The European Union adopted an EU-wide voluntary certification framework for carbon removals and carbon farming, and the EU renewable fuels of non-biological origin certificates became fully operational with the first recognised certification schemes.

Strengthen supply chain resilience and energy security. International innovation partnerships can help reduce supply chain vulnerabilities, for example in relation to critical minerals, by facilitating access to new resources. In 2025, several international co-operation frameworks incorporated innovation components.

- Canada, Australia and India launched a trilateral partnership with a focus on green energy innovation, strategic minerals development and AI.

- The United States and Australia agreed a Framework For Securing of Supply in the Mining and Processing of Critical Minerals and Rare Earths, including provisions to invest in minerals recycling technology.
- As part of the G7 Critical Minerals Action Plan, Canada announced around USD 14 million in support of international critical minerals R&D.

Ensure emerging and developing economies can participate in and benefit from energy innovation. Countries with limited fiscal capacity may struggle to invest in innovation. Joint initiatives can help spread knowledge, transfer technologies, build technical skills and provide financial and technical assistance. They can also facilitate the development and testing of technologies adapted to local contexts and needs, even when such technologies are already mature globally but still require local demonstration and scale-up.

- The Green Transition pillar of the EU Africa Initiative III is its largest funding area, with the equivalent of USD 260 million for climate adaptation, renewable energy, sustainable land use, and environmental resilience R&D. This is followed by R&D for technologies linked to critical materials (USD 200 million).
- LEAP-SE is a 6-year EU programme launched in 2025 involving about 22 partners from European and African countries with a USD 32 million budget for basic and applied research and experimental development carried out by consortia including at least two EU and two African Union partners (at least one of which must be from the institutional research sector and one from industry).
- France launched a Digital Energy Challenge in partnership with the European Union and its Digital and Green Innovation Action. With a budget equivalent to USD 1.1 million, it supports digital innovations that improve energy access, integrate renewable energy and enhance African energy operations.
- The Association of Southeast Asian Nations (ASEAN) Centre for Energy launched ASEAN Sparks, an accelerator programme for clean energy and climate technology start-ups across Southeast Asia, with support from the Japan-ASEAN Integration Fund and the United Nations Industrial Development Organization (UNIDO).
- The UK Government-funded Accelerate-to-Demonstrate Facility, operated by UNIDO, awarded funds to its first five pilots in Kenya, Namibia, Nepal, Nigeria, and Tanzania for lighthouse projects on innovative technologies, including on hydrogen, biomass gasification, smart grids, peer-to-peer energy sharing and lithium-ion battery manufacturing. A second call was launched in May 2025.
- India and Sweden announced the India-Sweden Industry Transition Partnership to develop pre-pilot projects in steel and cement in India, with selected projects focused on CCUS, including syngas production from waste CO_2 streams, electrification of steel and ironmaking, and AI.

Remaining policy gaps and priorities

The State of Energy Innovation 2025 identified ten key priorities and policy gaps requiring increased attention from governments and other stakeholders to address emerging energy innovation challenges. One year later, this edition's findings and the stakeholder survey conducted for this report indicate some progress in several areas, but additional efforts are still needed.

Energy innovation investment

- **Raise public energy R&D and demonstration spending**. As highlighted in Chapter 2, spending on energy innovation is rising faster than total R&D across all sectors but this has not translated into higher public energy R&D in 2025. Survey respondents highlight the scarce funding resources available for early innovation stages and to bridge the "valley of death". Governments may consider aiming to restore energy R&D intensity towards the 0.1% of GDP level reached by IEA Members in the early 1980s. This would encourage private co-funding and strengthen competitiveness. Data gaps, especially for non-grant support, continue to prevent accurate assessment of public funding levels.
- **Maintain stable support through economic cycles.** Technologies that take many years to develop are particularly vulnerable to economic downturns and changes in public spending priorities. This uncertainty increases investment risks and affects where innovators choose to develop and scale up. Clear, long-term policy direction and predictable support help to sustain private investment in these capital-intensive technologies. As shown in this chapter, priorities evolve over time: fusion energy and AI-led innovation are attracting more attention worldwide, potentially creating uncertainty for researchers working on topics that are less "hot" right now, but could tap into domestic competitive advantages.

Policy design and delivery

- **Maximise innovation impact from public investments**. Governments are using a wide range of tools to support innovation, including grants, prizes, loans, guarantees, equity investments and non-financial support. For many projects, public support is best used to facilitate private investment by taking on certain risks at lower cost and signalling project credibility. In their national strategies, countries such as Germany and Korea have set ambitions to move towards performance-based funding systems, linking support more closely to the achievement of clear milestones to improve the impact of public spending. Systematic policy evaluation can help governments improve and focus interventions and ensure value for public spending (Chapter 5).
- **Tailor support to the innovation needs of each technology from the outset**. Support schemes should reflect the distinct technological, system integration and

physical[16] risks that technologies face across their innovation lifecycle, particularly for start-ups without proven track records. For modular equipment, a key challenge is often securing the first orders and advance payments to start manufacturing. The EIB and other public banks are increasing the availability of counter-guarantees that support cash flow. Larger industrial projects, by contrast, often require grants or other support to help build first-of-a-kind plants or scale up production. New programmes in Canada, Europe and the United States for critical minerals processing, low-emissions fuels and CCUS address this issue. Some of these technologies also depend on dedicated new networks, such as for hydrogen and CO_2 – however, there is less evidence of progress with early infrastructure planning to avoid bottlenecks in this area. Digital solutions typically require less capital and can generate returns more quickly, making private investment easier to mobilise and reducing the need for public support.

- **Foster markets that signal robust future demand for emerging clean technologies**. Even when technologies are technically proven, uncertain demand slows their deployment. Many countries have successfully used renewable energy auctions in recent years, and we see a welcome trend towards reserving part of the budget for less mature technologies to help first large-scale projects move forward, especially offshore. At the same time, new auctions are being introduced to support more emerging technologies, such as grid-scale storage, low-emissions hydrogen-based fuels, SAFs and CCUS. Governments can also use public procurement, their significant purchasing power, and standard-setting, to help create early demand for innovative technologies, though we estimate that more could be done in this area given its potential. Innovators also note that the lack of clear standards for new technologies can slow market creation; while international initiatives are starting to address this, stronger co-ordination could help accelerate markets.
- **Reduce bureaucracy and make funding easier for innovators to access**. Several countries are trying to reduce complexity, yet innovators still report frustrations with bureaucracy. These include complex application processes, high preparation costs and long approval timelines, all of which can tie up time and resources, and slow down innovation. As shown in this chapter, governments are taking steps to simplify processes and speedup decisions, including via one-stop-shop facilities, such as the EIB's TechEU platform, permanently open calls and agreements to recognise each other's evaluations. Funding schemes that support projects through sequential stages smooth the pathway for promising developers.

Access to research and testing facilities

- **Expand access to testing facilities and "living labs"**. Many innovators, from companies both large and small, need access to costly testing and demonstration facilities that would be prohibitively expensive for them to build alone. There are

[16] Physical risks are most relevant for technologies dependent on uncertain geological resources, such as geothermal energy.

examples of governments creating new shared research centres and improving access to existing ones to ensure better use of public assets, including in areas such as hydrogen and nuclear. International co-operation is particularly important for highly capital-intensive technologies like fusion energy and collaboration between public laboratories and start-ups is a growing feature of that sector. To maximise impact, dedicated research infrastructure strategies have been developed in countries such as China and Denmark.

- **Tap into AI-driven R&D opportunities**. Since publication of The State of Energy Innovation 2025, which included a focus chapter on AI for energy technology innovation, more governments are funding and co-ordinating activities to support leadership in this area. Canada, the United Kingdom and the United States are targeting speeding up technological development with AI, including with dedicated initiatives on fusion energy and battery materials. As emphasised at the IEA Energy Innovation Forum 2025, governments working together internationally can play a key role in enhancing researchers and innovators' access to critical AI infrastructure for new discoveries.

Global innovation capacity

- **Co-operate internationally on large-scale energy and industrial demonstration projects**. Joint efforts are needed to develop first-of-a-kind technologies and enable knowledge diffusion across countries, particularly for applications not yet at full commercial maturity, such as in aluminium, cement, steel, aviation and shipping fuels, and direct air capture (DAC) and other CDR technologies. However, in 2025, survey respondents noted reductions in support programmes in certain countries. Initiatives like Mission Innovation and IEA Races to Firsts can encourage progress, but stronger international collaboration and public-private partnerships are needed to develop a balanced portfolio of projects across regions and technologies, while ensuring lessons learned are shared. The achievements of international fusion energy projects show what such co-operation can deliver (see Chapter 7).
- **Strengthen energy innovation systems in emerging and developing economies**. This chapter illustrates examples of development co-operation supporting energy innovation in 2025, set against tightening official development assistance budgets. Expanding innovation capacity and fostering collaboration, among emerging and developing economies, and with advanced economies, remains key to modernise energy systems worldwide, while addressing pressing development challenges such as energy access, clean cooking and mobility. Many countries that lack access to high-quality R&D opportunities nonetheless offer unique opportunities for scaling up certain technologies, including CDR, low-emissions hydrogen or near-zero emissions steel, which rely on competitive low-emissions electricity costs and access to raw materials. The HyIron project in Namibia, highlighted in Chapter 1, shows promise in this regard.

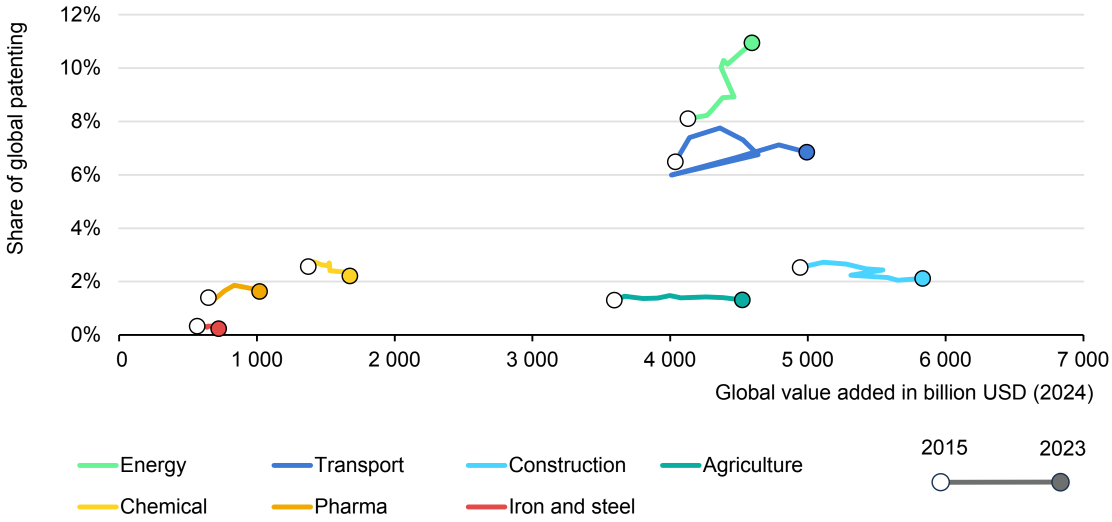
Chapter 5. Focus: Innovation for competitiveness

The 2025 Nobel Prize in Economics was awarded to three researchers who explained the importance of innovation in driving sustained economic growth. Their key contributions were the insights that engagement with science and the embrace of new ideas are fundamental to cumulative productivity gains, and that economic growth results from the displacement of superseded firms by those that innovate improvements. Where markets work well, the most competitive firms attract the most capital to grow their businesses, and in technology-based sectors the most competitive firms are those with the technologies that meet users' demands in the most affordable, reliable and fastest way. The award is a strong reminder that innovation must be at the centre of any strategy to promote firm-level competitiveness and economic growth.

With annual investment of USD 3.3 trillion and 76 million workers worldwide, the energy sector has outsized importance for the global economy. Energy spending represents around 8-10% of GDP annually. In some countries that export energy technologies and resources, the sector overshadows almost all others. An IEA estimate suggests that growth in energy technologies represented 10% of all GDP growth in 2023. Companies investing in innovation in energy efficiency have been found to have 15-18% higher labour productivity. Compared with other major economic sectors, energy represents a higher share of patenting activity, which grew steeply from 8% to 11% between 2015 and 2023.

It is little wonder, therefore, that governments pay close attention to the impact of energy on economic competitiveness. Many seek to harness energy technologies to provide a strategic advantage, whether by reducing energy prices for productive industries, attracting investment capital for new infrastructure, or exporting equipment and services. Such a strategy has innovation at its core. Long-term public investment in innovation is not merely a cost item, but a strategic enabler of competitiveness.

Patenting versus value added in selected economic sectors, 2015-2023



Note: Patenting shares are calculated on the basis of international patent families, each of which represents a unique invention and includes patent applications filed in at least two countries.
Sources: IEA analysis based on data from PATSTAT and Oxford Economics Limited (2025).

This chapter takes a three-pronged approach to exploring the link between enhanced energy innovation and competitiveness. It aims to increase understanding of the economic pay-offs, especially of public sector support to energy technology innovation, and identify specific examples of how emerging technologies today could address known competitive weaknesses. The first section reviews the evidence for economic returns from spending on energy innovation, such as through targeted energy R&D programmes. The second section illustrates the essential role that public support to innovators has played in creating whole new economic sectors based on disruptive energy technologies. The third and final section uses IEA analysis to translate this positive message into forward-looking priorities, based on known emerging technologies that have the potential to close cost gaps faced by manufacturers in key regions.

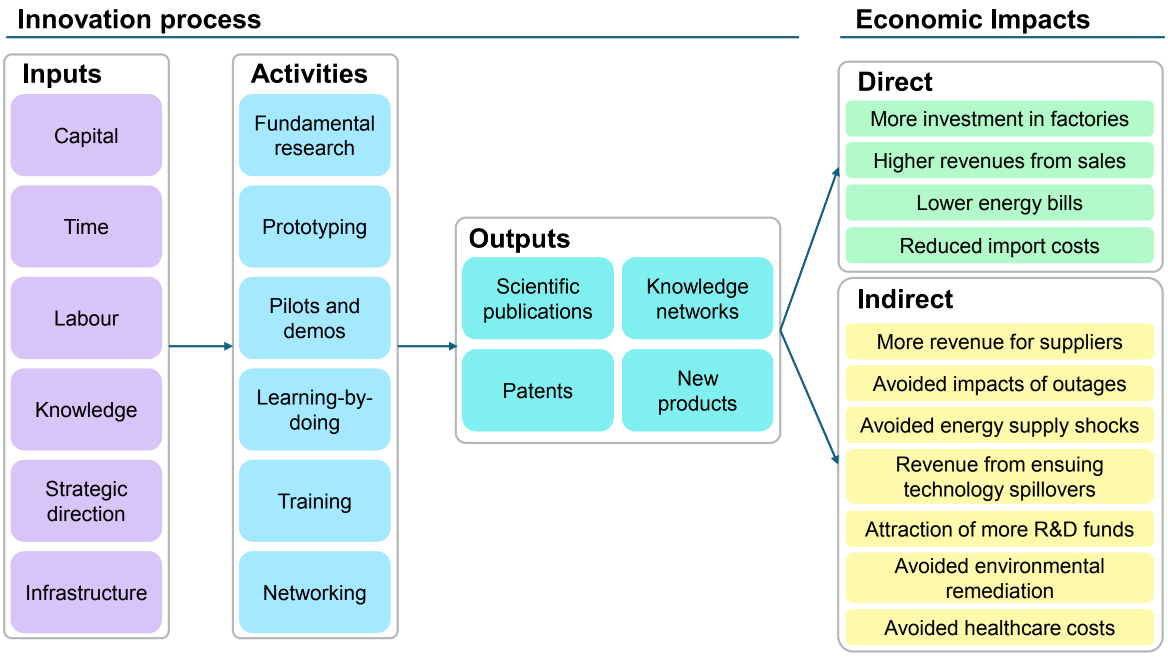
The economic pay-offs from public spending on energy innovation

Innovation generates economic returns to countries in a wide variety of ways, both direct and indirect.[17] For countries, these innovation returns raise the competitiveness of facilities in their territory that attract more capital to new products or face lower input costs. Direct economic impacts mostly result from

[17] While most benefits of innovation ultimately translate into economic benefits in one way or another, some are largely non-economic in nature, including improved knowledge about the world, environmental protection, safety or greater well-being from productive employment. This chapter is concerned with economic benefits and competitiveness.

businesses investing in facilities to produce the new technology, revenue from sales and the economic opportunities that accrue if this results in lower energy prices, or reduced import costs. Among others, indirect economic benefits include avoided economic shocks due to energy supply or equipment supply disruptions, avoided health and environmental remediation costs, and revenues from associated products whose invention was made more likely by an expanded stock of knowledge (also called "spillovers").

Inputs, activities, outputs and economic impacts of energy innovation



There is broad interest among policy makers in understanding the economic and competitiveness benefits of their innovation-oriented policies. They want to know the impacts of their spending on energy innovation for two reasons: to demonstrate value-for-money to taxpayers and financial ministries; and to understand which types of interventions are most likely to deliver their policy goals.

However, even the direct benefits can be difficult to measure. Much innovation does not result in an entirely new type of product but rather improves the efficiency or attractiveness of an existing one. In some cases, it combines two existing products in a new way. How to isolate the economic benefits of an incremental improvement as a share of total product revenues or investment is a daunting enough task, but doing this across a wide portfolio of products is even harder. Furthermore, some products perfected in one country, where the R&D took place, may be manufactured and marketed in another country entirely. Indirect benefits cannot be measured without uncertain assumptions and a sophisticated economic model. As a result, too little is known about the magnitude of the economic benefits of energy technology innovation, which makes it an area where more expert attention is needed.

Despite these challenges, there is evidence of the impact of energy innovation programmes. It can be grouped in three categories that are reviewed in the following sub-sections:

- Retrospective cost-benefit analyses
- Estimates of macroeconomic impacts of government programmes
- Evidence of the additionality of R&D tax incentives.

Retrospective cost-benefit analyses

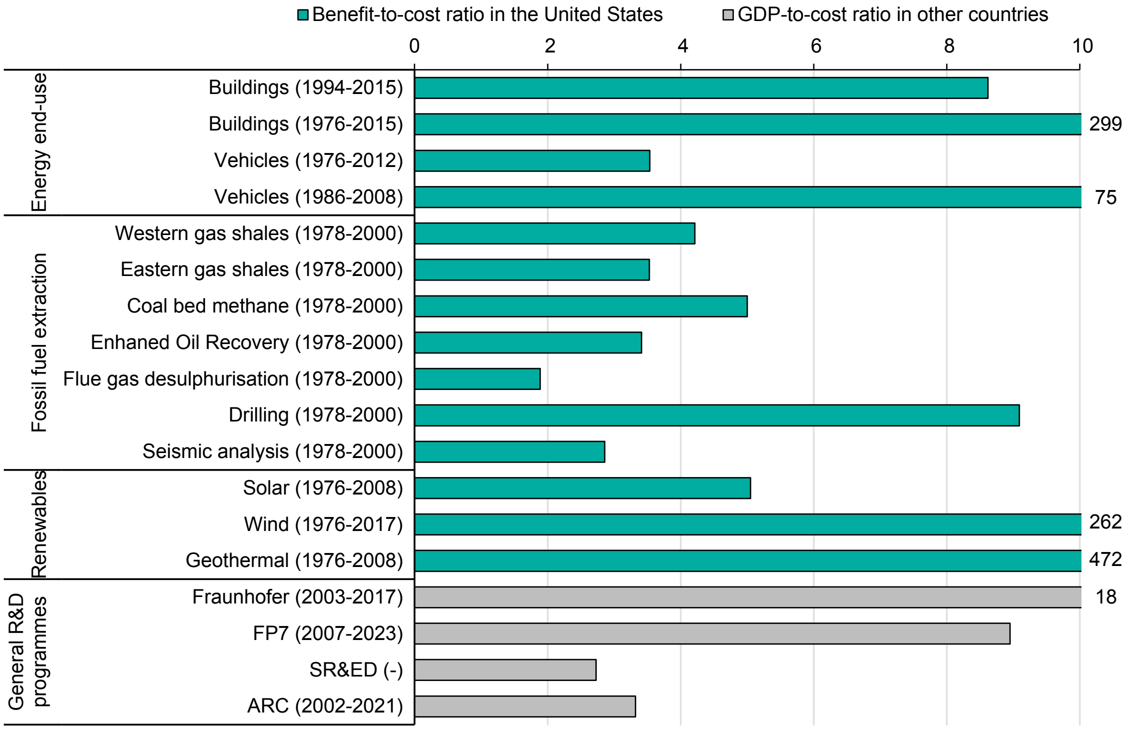
Cost-benefit analysis is one way to try to crystallise the impacts into a single metric – an economic one – and facilitate comparison between interventions with different cost levels.

The most complete retrospective cost-benefit evaluations are from the United States (see figure below). These have shown that direct benefits were at least three times greater than the costs in most cases, with several examples such as wind and geothermal resulting in several hundreds of dollars in benefits for every dollar of cost. Higher returns are typically seen for measurements over longer time periods after the start of the intervention, as benefits compound over time and are higher towards the end of the period studied. This corresponds to high internal rates of return. For example, for the R&D in wind (1976-2017) it was 15.4%, for solar PV (1975-2008) 17%, and for geothermal (1980-2008) 22%. Direct benefits included in these studies include:

- The value of fuel saved through higher vehicle efficiency, compared with vehicles that had not been improved by the innovations in question.
- Cost savings from a steeper cost decline of electricity generation technologies, such as solar PV or wind, compared with a counterfactual cost trajectory without the impact of the innovations.
- The value of incremental oil and gas production due to improved drilling.

Over the past decade, around USD 450 billion has been spent by governments on energy R&D. Assuming that this level of spending continues over the next decade, and using a conservative benefit-to-cost ratio of 4 for the direct benefits that will accrue from it over a 20-year period from 2016, gives an average net annual return of USD 180 billion per year by 2036.

Benefit-to-cost ratios for energy-related R&D programmes in the United States in comparison to ratios from general R&D programmes around the world



Notes: FP7 = 7th Framework Programme (2007-2013 general research programme from the European Union); SR&ED = Scientific Research and Experimental Development (tax incentive programme in Canada); ARC = Australian Research Council R&D funding; GDP = Gross Domestic Product. Fraunhofer is an applied research organisation with 75 institutes in Germany supporting private and public projects. Benefit-to-cost ratios do not consider a discount rate, which would lead to lower values. General R&D programmes cover more than energy technologies.

Sources: IEA analysis based on US Department of Energy (2025), European Commission (2025), Government of Canada (2025), European Commission (2024), ACIL ALLEN (2023), European Commission (2017), National Research Council (2001).

Several broader R&D programmes that are not energy-specific have been assessed in terms of the wider benefits to GDP compared to costs. These studies show benefit ratios that range from 3 to 18, supporting the likelihood that considering direct benefits only underestimates total economic benefits.

It is likely that these estimates underestimate even the direct economic benefits. Evaluations are typically conducted a few years after the programme ends. The benefits beyond the evaluation period, including from installations funded by the programme and still operating, are often not considered. In addition, these studies tend to cover the more quantifiable elements of energy innovation programmes – such as financial payments to innovators – and do not evaluate types of public support that are more diffuse. This kind of support can be impactful, and includes market creation policies that incentivise private innovation spending, support to research networks, intellectual property regimes, loan guarantees and prizes.

The indirect benefits can be even larger than the direct but are harder to quantify. One technology can have benefits that ripple across multiple industries. It is hard to demonstrate causality in the cases of higher dividends paid by companies or indirect jobs created in adjacent sectors. Indirect benefits can also arise when R&D programmes encourage more collaboration and higher densities of researchers from different disciplines. In the United States, for example, the so-called Research Triangle in North Carolina facilitates spillover effects and has played a leading role in developments such as big data, open-source software, 3D ultrasound and industrial LED lighting. As another example of indirect benefits, had there been no public R&D funding for batteries and electric vehicles from the 1990s onwards, battery electric vehicles might have not matured to today's level and oil demand today may have been 1.8 million barrels per day higher, nearly 2% of global demand, with more than 90% of the avoided demand in oil-importing regions. Identifying the share of the benefit, in terms of lower exposure to oil price volatility, resulting from given R&D programme is a difficult task.

To indicate indirect benefits, other metrics are sometimes employed. For example, the US Advanced Research Projects Agency for Energy (ARPA-E), which supports high-risk and potentially high-reward R&D projects, tracks the intellectual property registered, the numbers of companies formed to commercialise funded technologies, and the valuations of the companies. Since 2009, the USD 4.2 billion provided to over 1 700 projects delivered 173 companies, 36 "exits" (acquisitions or stock exchange listings) with combined market valuations of more than USD 22.3 billion and 468 licenses. Productivity gains have also been estimated, but not for energy R&D specifically: in the United States, a 1% decline in public R&D spillovers was estimated to lead to a 0.17% decline in firm productivity. Recipients of European Commission R&D grants were found to have increased employment levels by 20%, and their turnover and total assets by 30%, compared to comparable non-funded firms.

What if governments did not support energy innovation?

When assessing the impacts of public energy R&D policy, finding an appropriate counterfactual is important, but tricky. At a global level, the counterfactual is an absence of public funding directed to the energy technology challenges. In such a world, firm-level competition would spur some innovation activity and some research institutes with broad-based funding would choose to focus on energy topics. However, there is an extensive body of research explaining why this level would be unlikely to provide a sustainable competitive advantage. Economists point to market and system failures that lead to systemic underinvestment in R&D by firms. These include the fact that knowledge is hard to fully privatise compared to other assets, the time lag between R&D and significant revenues, and the lack of information about the global state-of-the-art. These issues are exacerbated in the case of public goods such as environmental protection and networked utility services like electricity. For the energy sector, the value of emissions reductions mainly accrues to the public rather than to individual customers, development timelines can be especially long, regulations present higher costs of market entry, co-ordination challenges along infrastructure-heavy value chains raise risks, and some technological problems are simply too big for a company to tackle alone. Fusion energy provides an example of such issues, especially the high and risks costs of experimentation (Chapter 7), but floating liquefied natural gas and next-generation geothermal energy also owe their present maturity level to public funding (see the case studies later in this chapter).

A tougher problem is to assess a counterfactual estimating what would have happened if a single government, or several governments, had not allocated budget to energy R&D. For example, supposing that IEA Member governments had collectively spent nothing on solar PV R&D or scale-up since 2015, assessing whether the trajectory of cost declines would have been different, given China’s outsize contributions to the global learning rate. The nature of innovation means that knowledge flows relatively quickly across borders – through publications, co-operation and trade – and allocation of impacts to individual programmes is difficult. To address this, evaluators may look at the fortunes of recipients of dedicated funding in the period after the project and make assumptions about the balance between the influence of the new knowledge on non-recipients versus the influence of external knowledge on recipients.

Estimates of the macroeconomic impact of R&D programmes

Another approach to evaluating economic impacts is to use models to simulate the different ways in which publicly funded innovation influences the economy. The European Union has used such an approach for its EU-level R&D funding programmes. Evaluators concluded that, on average, they stimulate EUR 0.28 of additional public investment and EUR 0.85 of additional private investment per euro of public EU R&D spending. Other studies found that the added value of performing the research across European countries was 15-20% higher than if the same money had been spent by countries individually. These insights have subsequently been used in forward-looking models to estimate that recent programmes could deliver EUR 4 to EUR 13 of GDP growth for every euro invested, which represents an internal rate of return of 26-37%.[18]

Performance indicators for EU multi-year R&D programmes

Framework programme	Leverage effect	Overall benefit	Implied internal rate of return
7 (2007-2013)	Direct: 0.85 (private sector), 0.28 (national funds), 0.42 (average) Indirect: 0.64 (average)	GDP-to-cost: 8.8 (2007-2030)	32%
8 (2014-2020)	Direct: 0.15 (applied research), 0 (basic research)	GDP-to-cost: 6.8-12.9 (2014-2040) based on sensitivities with an average of 6.9	26-37% (2030), 32% (2050)
9 (2021-2027)	Direct: 0.15-0.35 (applied research), 0 (basic research)	Benefit-to-cost: 6.1-6.3 (2021-2045) GDP-to-cost: 4-11 (2045)	-

Notes: Evaluations of Framework Programmes 7 and 8 are ex post; the evaluation for 9 is interim. Framework Programme 8 is also known as Horizon 2020. Framework Programme 9 is also known as Horizon Europe.
Sources: European Commission (2025), European Commission (2024), European Commission (2017).

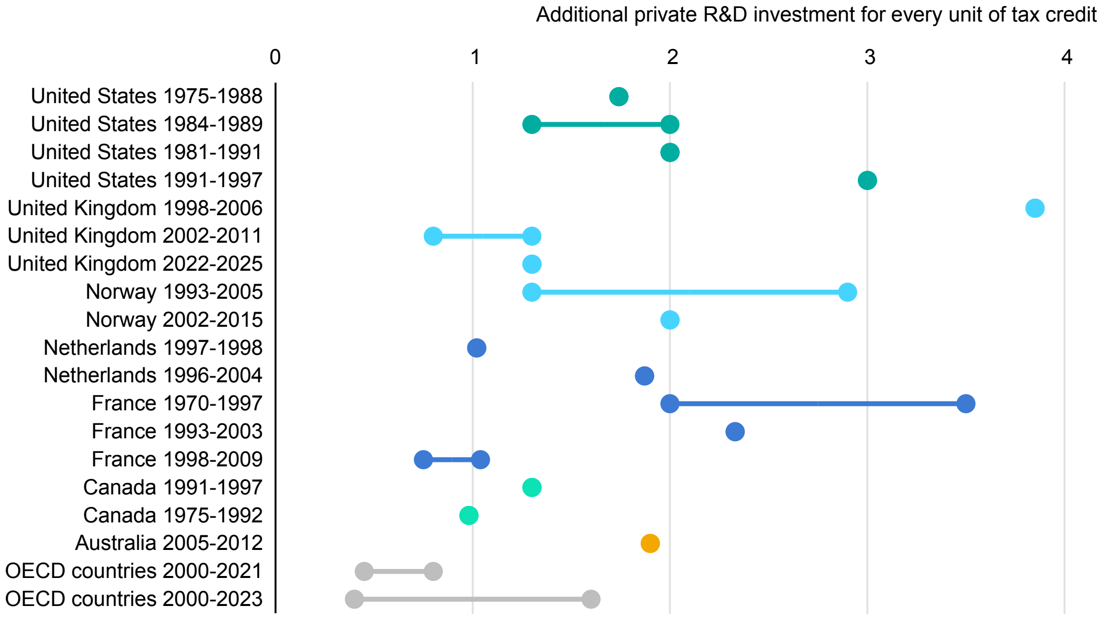
Evidence of the additionality of R&D tax incentives

Other studies have assessed the economic impacts of tax incentives that encourage firms to spend more on R&D by reducing the effective tax rate for these activities. In 2023, 55% of the financial support for business R&D, on average, was provided through tax incentives across 38 OECD Member countries, and more than 80% in Lithuania, Ireland, Colombia and China (Chapter 4). The impact of R&D tax credits has been estimated in terms of the additional private R&D expenditure (inputs to innovation) they trigger, higher firm-level productivity, and changes to the revenues of profits of firms (outputs from innovation). Studies of

[18] To project how innovation might impact GDP, and therefore set objectives for R&D programme outcomes, macroeconomic modellers consider a cascade of economic mechanisms. This begins with estimating growth in a "knowledge stock" variable and how it influences productivity and performance, followed by changes in demand for product and services. In turn, this can support more production of goods and can change trade balances. Each of these modelled mechanisms is underpinned by assumptions based on historical data and largely assumed to be constant in the future. The results generally indicate that GDP impacts of a given intervention initially relate to a higher investment phase, including stimulated private spending on innovation, including R&D, followed by a phase in which the impacts are higher and related to manufacturing, purchases and trade. Thereafter, the impacts in the model results fade due to saturation effects or technologies being superseded by subsequent innovation. The models do not represent the energy sector in detail, nor the potential for discontinuous technological change that reorients international patterns of fuel or material demand.

the impacts on innovation inputs have found that firms that take advantage of the tax break typically increase their R&D spending by a similar amount to the government contribution, thereby attracting private capital for R&D that would not otherwise have been spent. Furthermore, public R&D support triggers innovations that lead to environmental benefits.

Retrospective quantification of additional private R&D expenditure triggered by R&D tax credits across OECD Members countries



Notes: Studies presented here use one of two approaches: top-down analysis using a macroeconomic model with aggregated sectors and bottom-up analysis using firm-level data to compare companies receiving tax incentives with a control group. 2000-2023 study is based on 22 OECD countries with the lower and upper bound representing large and small firms respectively. 2000-2021 study is based on 19 OECD countries. R&D tax credits cover more than energy technologies. Values greater than one indicate that R&D tax incentives promote additional investment in comparison to the counterfactual scenario. In contrast, values lower than one mean that part of the foregone tax revenue is substituting private financing.

Sources: IEA analysis based on Appelt et al. (2025), How effective are R&D tax incentives? Reconciling the micro and macro evidence; DESNZ (2025), UK Net Zero Research and Innovation Framework Delivery Plan: Progress Report 2022 to 2025; OECD (2023), The impact of R&D tax incentives: results from the OECD microBeRD+ project; Holt et al. (2021), The additionality of R&D tax policy: Quasi-experimental evidence; Benedictow et al. (2018), Evaluation of the SkatteFUNN, Guceri and Liu (2017), Effectiveness of fiscal incentives for R&D: Quasi-experimental evidence; Laredo et al. (2016), Chapter 2: The impact of fiscal incentives in R&D; Guceri et al. (2015), Tax incentives and R&D: an evaluation of the 2002 UK reform using micro data; Klassen et al. (2004), A cross-national comparison of R&D expenditure decisions: tax incentives and financial constraints.

There are no examples of R&D tax incentives for energy R&D only, which means that the results of these studies can be used only under the assumption that energy companies behave in line with other sectors. While this assumption is broadly justifiable, it has been found that the benefits can be slightly lower in high-tech sectors than in mature industries that promise lower potential for spillovers and competitiveness in emerging industries. Furthermore, impact is assessed to be greatest for small firms, which are often further from the technological frontier than large firms, but which could potentially contribute step-changes in competitiveness if they scale-up. However, they tend to face more financial constraints, making the application costs more burdensome and their uptake of R&D tax incentives lower.[19] Targeting smaller firms, such as start-ups, could be a policy response, and small and medium-enterprises (SMEs) already receive more favourable tax treatment for R&D expenditures in several OECD countries.

R&D tax incentives and R&D grants have been found to lead to similar levels of additional private R&D expenditure; there is no clear evidence that one is more effective than the other.[20] Tax incentives can be attractive for their lighter-touch administrative requirements and can be more effective for incremental development, but do not allow innovative activity to be directed towards identified industrial weaknesses or competitiveness in a specific technology area. Direct subsidies can lead to higher returns over the long term, whereas tax incentives allow firms to expand activities in areas with higher returns in the short term. In addition, R&D grants have been found to generate higher impacts among firms in the manufacturing sector in particular, and to incentivise innovations with an environmental benefit. However, there is some evidence that tax incentives are effective at boosting the innovation impact of firms that have already undertaken R&D work with the support of public grants: the two types of support can therefore work together and, on average, increase the impact compared to the two tools in isolation.

Insights for improved evaluations of economic benefits

There is significant appetite for robust evidence of how public support for energy technology innovation delivers benefits for competitiveness. While the benefits are intuitively known by practitioners in the sector, quantified benefits are critical for communicating the importance of these policies to decision-makers and helping them chose between options for public budgets. As shown by results presented in this chapter, methodologies exist for research impact evaluation and its economic benefits, alongside compelling case studies, but are not widely applied.

Given the challenges of gathering data and attributing causality, there is a strong case for governments and other evaluators of energy innovation policies to share regular updates on approaches and results. This could cover several key considerations:

- **Counterfactuals and baselines**. It is difficult to evaluate whether an initiative was successful if its objectives were not clearly laid out in advance. For some programmes, *ex ante* impact assessments have been performed that state both

[19] This is consistent with findings from Appelt et al. (2025), OECD (2023), Benedictow et al. (2018), Laredo et al. (2016), Castellaci et al. (2015), Kasahara et al (2014) and Labeaga et al. (2014).
[20] OECD (2025), OECD (2023), Dimos et al. (2022).

the metrics and the expected impacts that could be evaluated by ex post evaluations. Examples include impact assessments for US national R&D institutions' work on vehicle technologies. To date, countries have taken quite different approaches to answering the question "what would have happened without the intervention in question?". For example, Norway assumes market penetration as a share of the technical potential or total market size, which might not be directly correlated to the research carried out. This suggests an opportunity to establish best practices for each approach, if not standardisation.

- **Timing**. The largest impacts of innovation spending do not accrue until many years or even decades after the intervention and can have enduring long-term benefits. However, as time passes, it becomes harder to gather data about funding recipients and attribute impacts. It is therefore important to put in place a system for data gathering at the outset of the intervention and in the years after it concludes. In addition, it can be valuable to gather initial insights into a variety of outputs and outcomes in interim evaluations during or soon after the programme is completed. These can be designed to guide decisions about how to design the next instruments before the full longer-term evaluation is made.
- **Scope**. It is important for cost-benefit analyses to be comparable and therefore clear about the way in which direct and indirect benefits have been measured, and over what timeframe. Whether the evaluation is limited to a single intervention or the combination of several is also a key decision. One finding of prior studies is that attribution to a single intervention is rarely possible, and that innovation impact is generated by different instruments working together, including policy measures to spur commercial technology uptake, such as regulations and standards.
- **Metrics**. Impact can be measured in economic terms where possible. Other metrics are nonetheless instructive to show trends over time or where they allow direct comparisons between programmes of outputs that are known to translate into competitiveness outcomes. For example, spillover effects can be tracked using patent citation data. Jobs, wages, capital expenditure, launch of new products, licensing of intellectual property, scientific publications, company creation and fundraising may help to inform conclusions about knock-on impacts.
- **Methods**. Cost-benefit analyses and estimation of macroeconomic modelling are just two different classes of methodology. There is currently no agreed ideal method, although using multiple approaches can be valuable to address different shortcomings of each method. Theory-based evaluations (an explicit theory of change or logic model that explains the causal relationship of how outcomes are achieved), experimental evaluations (testing the existence of the causal relationship through surveys or trials). An underused approach to evaluating impact is to follow outcomes for a cohort of researchers or projects that did not receive funding support. To isolate the impacts of policy interventions, randomised controlled trials of policy interventions are proposed.

Characterisation of retrospective assessments of energy R&D programmes

Technology	Period of intervention	Evaluation year	Counterfactual	Method	Metrics
O&G production and upgrading	1978-2000	2001	• Lower O&G production estimated with a reservoir model with changes in domestic oil prices from an equilibrium model • Lower efficiencies for exploration, production, refining • No new technology is introduced and only conventional industry technologies are available	Based on expert input and discussions with industry (e.g. 35% of production from Western gas sands in the 1978-2005 period)	• Incremental production • Knowledge reducing exploration, drilling, completion costs • Environmental (lower pollution) • Security (increased oil reserves)
Solar PV	1975-2008	2010	• Crystalline silicon (c-Si) with higher cost and shorter lifetime in agreement with industry for economic benefits • Thermal generation assumed to be the counterfactual to estimate environmental benefits	• Alternative cost trajectory from industry in the absence of DoE support • One-sixth of total environmental and security benefits	• Economic (cost and lifetime for domestic production and cost for exports) • Environmental (air pollutants) • Security (displaced thermal generation) • 274 patents and 900+ publications; top producers • IRR of 17%
Onshore wind	1976-2017	2020	6-year delay of cost reduction and deployment vs a scenario with private R&D and public R&D from other countries based on expert judgment	80% attribution to the DoE based on cost sharing with industry	• LCOE times capacity considering the 6-year delay • Avoided health incidents from lower PM exposure from lower thermal generation that would be displaced by wind • IRR of 15%
Energy storage for hybrid and electric vehicles	1999-2012	2013	A battery with worse performance (6-year delay of industry-wide R&D) and lower deployment (based on survey of 54 experts)	• Based on expert survey • 30-35% of the increase in battery life and energy density and lower cost • 64% of deployment from 1999 to 2012	• Gasoline displaced (cost, environment and security) • 112 patent families, 2337 publications and presentations • IRR of 18%

Technology	Period of intervention	Evaluation year	Counterfactual	Method	Metrics
Advanced combustion engine	1995-2007	2010	Lower fuel efficiency trajectory based on industry input	• 100% attribution considering research costs (too high for the private sector) and co-ordination needed	• Fuel efficiency (cost, energy security, environment) • 109 patent families, 112 publications • IRR of 63%
Geothermal	1980-2008	2010	Next-best alternative (affecting productivity, cost, efficiency) and delay (2 years) in technology penetration based on interviews and research	• 50% of economic benefits (interviews and research) for enhanced drilling • Acceleration of 6-60 months for binary cycle • 20-80% for reservoir models (interviews)	• Cost reduction • Operating efficiency and productivity • Environmental (air pollutants) • 90 patent families, 3000+ publications • IRR of 22%

Notes: O&G = oil and gas; IRR = internal rate of return; LCOE = levelised cost of electricity; PM = particulate matter.

Case studies: public sector contributions to transformational energy technologies

Energy innovation has launched whole new sectors of private activity, founded upon new products and techniques brought to the market by major corporations. While these corporations are quick to brand their new activities and take credit for their contributions, the role of the public sector in the innovation process is often underappreciated. Corporate innovation typically builds upon foundations laid by sustained public investment in R&D, and public support for demonstration projects and the earliest stages of adoption. Open access data, publicly funded demonstration projects, and early-stage technology validation lower the costs and risks to be borne by private capital. Taxpayer-funded research institutions and scientific excellence, accompanied by targeted public-private partnerships, have long been an effective model for energy sector innovation.

In this section, four case studies are explored to reveal the combined roles of the public and private sectors for arriving at today's level of success. The technologies considered are floating liquefied natural gas (FLNG), next-generation geothermal, lithium-ion batteries and grid-forming inverters. Each case demonstrates how targeted public support has been indispensable for reducing risks, generating critical technical knowledge, and creating the enabling conditions for market-led innovation. In each case, there has also been a strong role for international co-operation or, at the least, sharing of the innovation costs between countries that funded sequential projects. The continuity of public R&D support, whether in a single region or across borders, can be a critical factor in sustaining the innovation pipeline and allowing good ideas to successfully reach maturity.

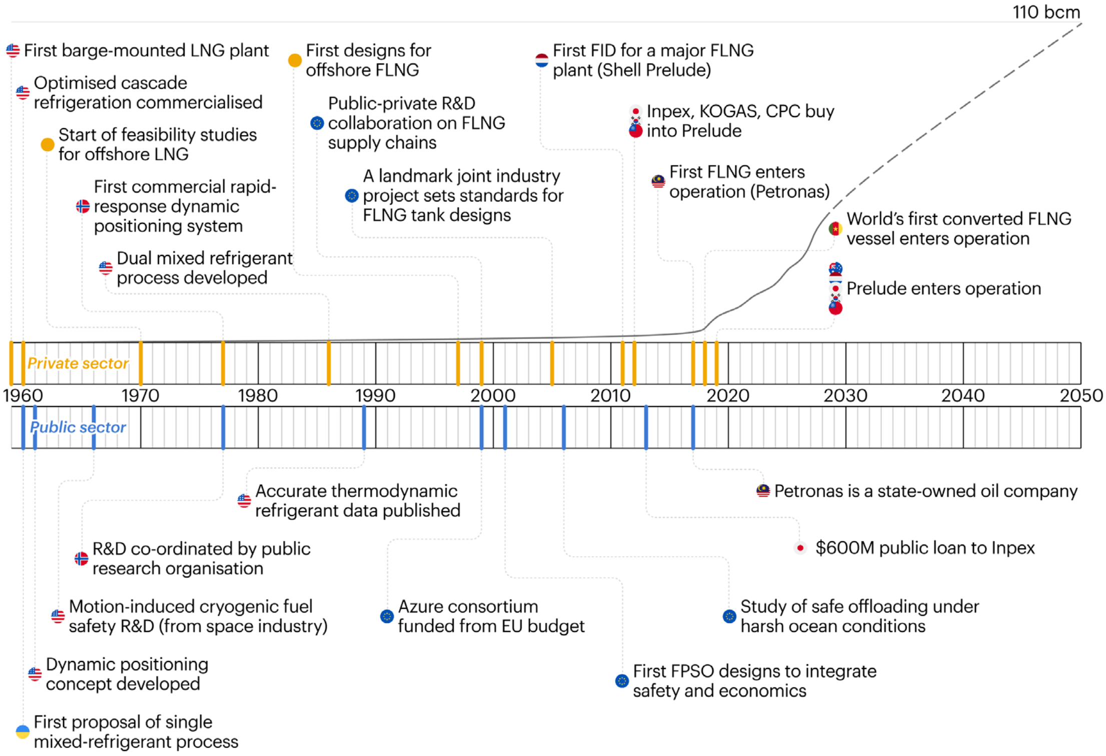
Floating liquefied natural gas

Turning natural gas from a local resource to a globally traded fuel was a feat of engineering that was accompanied by extensive co-ordination between the earliest buyers, sellers and investors, and the creation of entirely new standards and contracts. Although the first recorded liquefaction of methane was in 1885, sustained R&D effort over decades was required to safely liquefy, store and transport gas at -162°C, build equipment to withstand large temperature swings, and create markets that could support the large infrastructure investments that drove long-term cost reductions. The first liquefied natural gas (LNG) cargo was shipped in 1959, and the first floating liquefied natural gas (FLNG) project loaded its cargo in 2017. Today, LNG is a global market with 560 bcm LNG traded in 2024. With projects under construction, it is expected that the LNG capacity globally will reach over 800 bcm by 2030. Of this, about 50 bcm would come from the 15 FLNG projects already in operation or construction, and 60 bcm from FLNG at earlier development stages.

The early stages of LNG innovation took place in public research institutions. Liquefaction technology advanced quickly in the first half of the twentieth century, initially to extract helium from natural gas and then use it in cryogenic apparatus for experiments, communication and radiation detection. From 1908, researchers at the public University of Leiden in the Netherlands, the US Department of the Navy, the US Navy Bureau of Aeronautics, the US Bureau of Mines and the US National Bureau of Standards, as well as the private Massachusetts Institute of Technology, furthered the research. Methane was liquefied as a by-product of extracting helium for military purposes in World War I and added to natural gas supplies. Concurrently, government researchers in Ukraine built experimental liquefaction and storage systems in the 1930s to power machinery with LNG. The technology developed in these public programmes enabled the first patent on large-scale liquefaction in 1937, followed by the construction of the first pilot LNG facility by a private gas company in West Virginia, United States, then a commercial facility in East Ohio that stored gas to meet high peak demand. Liquefaction processes were improved in 1960s, with Phillips Petroleum focusing on optimised cascade liquefaction, and Air Products leading the mixed refrigerant processes – first developed at the Ukrainian Gas Research Institute – forming the basis of today’s LNG industry.

The UK government, via the UK Gas Council, funded the first trans-oceanic LNG trial, Methane Pioneer, in 1959, which was operated by three private firms – Conoco, Union Stockyards and Shell. No private firm was willing to carry the technical, commercial, and safety risks of a first-of-a-kind project. After the demonstration of an LNG transport from the United States to the post-war energy-constrained United Kingdom, Gaz de France (a French state-owned company) and the UK Gas Council signed long-term contracts with Algeria, enabling the world’s first export-oriented commercial LNG plant at Arzew in 1964. By 1969, LNG trade expanded to include routes from the United States to Asia, drawing in additional companies who worked on technological improvements. During and after this period, publicly funded research continued, and focused on safety, following deadly accidents in 1944 and 1973 in the United States. Governments also funded work on LNG bunkering (United States) and cold-energy efficient heat integration (Japan).

Timeline of the floating liquified natural gas innovation journey and global deployment, along with key public and private contributions, 1960-2050



Notes: LNG = liquefied natural gas, FLNG = floating liquefied natural gas, FID = final investment decision, EU = European Union, FPSO = floating production storage and offloading.

The next major technological challenge of placing the liquefaction process on a floating barge was proposed as early as 1959 and pursued in the 1970s. The promise of FLNG was the development of remote or stranded offshore gas fields that could not justify pipelines or onshore liquefaction. However, the benefits of lower unit gas field development costs, shorter times to market and the ability to relocate the liquefaction facility would come only if the entire onshore LNG process could be shrunk to a fraction of the footprint and designed to withstand continuous vessel motion. This required the development of several adjacent technologies, including: fast-response, automated dynamic positioning systems for vessel navigation; compact, lightweight liquefaction processes for marine environments (including adaptations of single and dual mixed refrigerant techniques); and a better control of tank safety and offloading under variable metocean conditions.

Although a small-scale barge-mounted plant had been successfully used in shallow coastal waters in the US State of Louisiana in 1959, engineering designs were not begun for large offshore facilities until the 1970s and the prospects for commercial projects did not materialise until the 1990s. In 1999, it was a project co-funded by the European Commission, called Azure, that led 13 private companies to co-operate on the technical design and testing of the engineering components. The European Commission subsequently funded further private work on full-chain floating systems – so-called floating production, storage and offloading (FPSO) – and safe offloading. Prelude was the first FLNG project to reach final investment decision in 2011, with a small injection of public finance to help the owners and suppliers (the suppliers were primarily from France and Korea) to overcome the challenges of financing a new technology at scale. While Prelude was initiated and initially financed by Shell, a private company, other consortium partners subsequently bought a third of the shares to complete the financing, including state-owned companies from Korea (KOGAS, 10%) and Chinese Taipei (CPC Corporation, 5%). The Japanese government lent USD 600 million to Inpex, a private Japanese firm, so it could buy its 17.5% share. The project also triggered a landmark study on the regulatory frameworks and safety by the Australian government in 2015.

The next FLNG project to enter construction, and the first one to start offloading cargoes in 2017, was owned and operated by the Malaysian state-owned company Petronas. For the third project – also the first LNG carrier to be converted into an FLNG vessel – 80% of the construction cost for the Cameroonian facility was covered by China's state-owned shipbuilder, CSSC.

The early projects in both LNG and FLNG relied on public funding to share the risks of new technology and untested markets. In addition, they were reliant on international government efforts to develop and agree regulations and standards. Continued innovation is underway, for example Canada's co-funding of the indigenous-led Cedar LNG project to reduce its emission intensity. Other publicly funded research focuses on advancing modularisation and improving environmental performance.

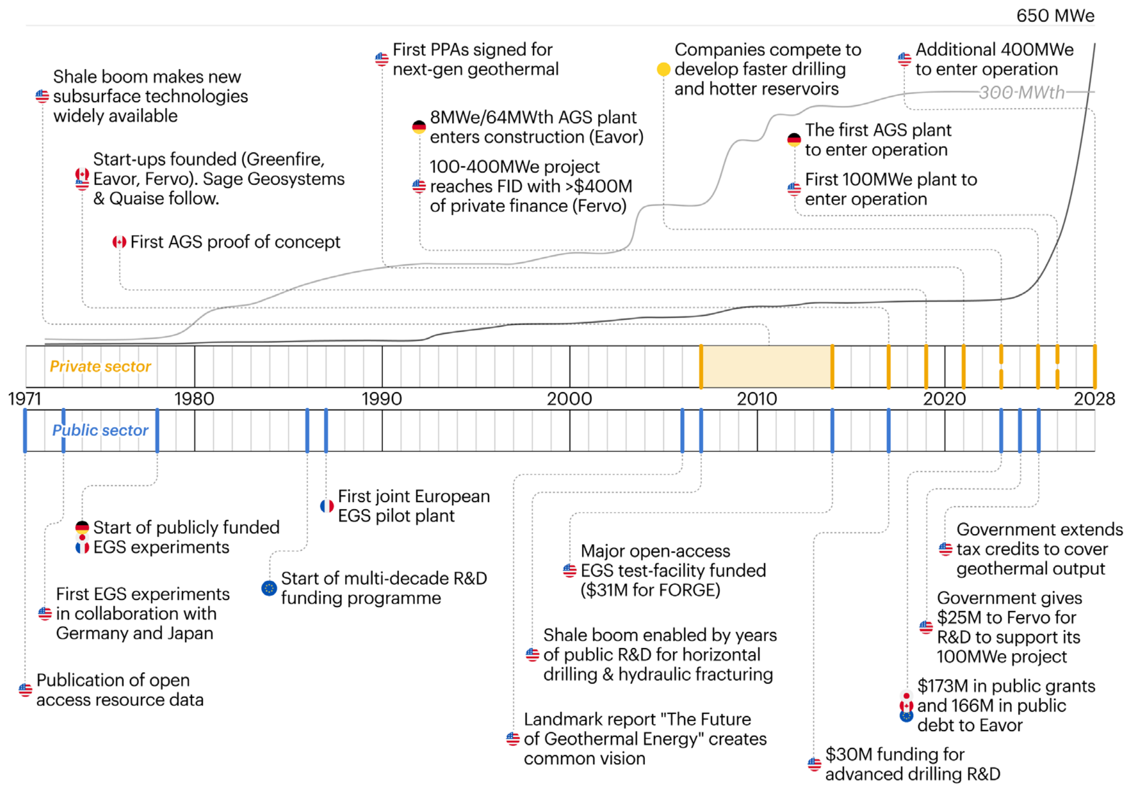
Next-generation geothermal energy

For power generation, most geothermal energy is concentrated in locations where high-temperature steam can be easily accessed from underground formations close to the surface. This type of geothermal resource – called hydrothermal – has been exploited for over 100 years. Since the 1970s, researchers have pursued the promise of extracting renewable geothermal energy, potentially enabling its use almost anywhere in the world. However, next-generation technologies[21] raised financing for commercial-scale delivery for the first time only in 2023. High risks of investing in wells with low-quality resources, high drilling and well

[21] This term encompasses both enhanced and advanced geothermal. Enhanced geothermal systems (EGS) involve expanding the existing geothermal reservoir capacity or creating new reservoirs, by increasing hot-rock permeability through hydraulic, thermal or chemical stimulation. Advanced geothermal systems (AGS) involve the drilling and sealing of deep, large, artificial closed-loop circuits underground – these systems act as subsurface heat exchangers in which a fluid is circulated and heated by surrounding hot rocks (without chemically interacting with them) through conductive heat transfer.

construction costs, as well as concerns about induced seismicity slowed commercial scale-up and deterred private capital over several decades. A single failed well in a low-margin business can derail project economics, unlike in oil and gas, where profitable discoveries can be sufficiently lucrative to offset the cost of dry holes.

Timeline of the next-generation geothermal innovation journey and global deployed capacity, alongside key public and private contributions, 1971-2028



Notes: AGS = advanced geothermal systems, EGS = enhanced geothermal systems, PPA = power purchase agreement, FID = final investment decision, MW_e = megawatt electric, MW_{th} = megawatt thermal

In the early days of next-generation geothermal, no large private geothermal companies were at the forefront of research and technology development. For the private sector, the full risks and the costs associated with exploration, drilling and stimulation operations were too high to be justified by the uncertain future pay-off from potential utility revenues. Public finance was essential.

Government-funded tests and field experiments were undertaken from the early 1970s to 2000s in the United States (Fenton Hill and East Mesa), Germany (Bad Urach, Falkenberg, Neustadt-Glewe and Groß Schönebeck), France (Le Mayet and Soultz-sous-Forêts) and Japan (Hijiori and Ogachi). Feasibility studies and field tests were also funded in Philippines, Australia as well several other locations in Europe and the United Kingdom. Government-funded research programmes and national mapping surveys, such as those mandated by US law in 1971, 2005, 2007 and 2020, and reviews of the state-of-the-art, such as the 2006 US The Future of Geothermal Energy report, helped disseminate subsurface knowledge. This reduced the risk of spending capital on drilling in suboptimal locations.

Since the mid-2000s, technology developed in the oil and gas sector for hydraulic fracturing and horizontal drilling in shale resources provided a much more sophisticated technological basis that could be transferred in part to next-generation geothermal. The role of public research in the development of these technologies from the early 1970s to the early 2000s is documented elsewhere. Public research programmes helped the private sector to scale up the techniques, drive down drilling and completion costs, and establish an ecosystem of skilled workers and service provision.

The combination of recently acquired oil and gas sector knowledge with the prior work on next-generation geothermal enabled the first large-scale trials to be planned with the US Department of Energy from 2015 onwards. Proven subsurface technologies could be applied to deeper, hotter, and more complex geothermal reservoirs at this point. A primary example is the Frontier Observatory for Research in Geothermal Energy (FORGE) project, an open access field lab that makes all results, datasets and stimulation experiments publicly available. Public R&D grants from Geothermal Technologies Office accelerated stimulation, monitoring and learning-by-doing, and funded start-ups looking to commercialise the technologies. One such start-up, Fervo, reported a 70% year-on-year reduction in drilling costs. FORGE has played a pivotal role in allowing companies, investors and researchers to see demonstrated performance in real conditions; a prerequisite for attracting private investment.

Other public interventions supported the nascent next-generation geothermal sector. Testbeds, shared data and risk-sharing mechanisms allowed companies such as ORMAT, Calpine, Fervo, Eavor, GA Drilling and Quaise to attract private capital and iterate their innovative approaches rapidly. This included:

- Grants from the US Department of Energy for improving the efficiency of drilling operations (2018), and reducing drilling costs by 25% (2022), and multiple grants[22] from the US Advanced Research Projects Agency–Energy (2018-2024) for advancing next-generation geothermal know-how.
- Canada Growth Fund investment of up to USD 100 million for Eavor (2025), building on an earlier USD 65 million in funding (2023).
- Numerous grants from the European Commission, starting in 1981, for investigating new exploration methods, soft stimulation, deep-drilling advances,

[22] See MW Drilling, High-T Optical cables, REPED250, SUPERHOT and Electro-Hydraulic Fracturing for EGS

well materials, high-temperature electronics and well components.[23] In 2023, the European Innovation Fund provided a USD 100 million grant to Eavor for the first-of-a-kind Geretsried AGS project.

- Demand-side measures provide more certainty of future energy sales if technology scale-up is successful. Indonesia, Türkiye, Germany and Chinese Taipei have feed-in-tariffs that target geothermal energy. Similarly, clear cost and scale targets are set by a US public defence procurement programme.

While next-generation geothermal energy is still not a widespread business – the first commercial plants are under construction – there are high expectations for the coming years. Without any significant corporate backers, the technology has been largely developed in research institutes and then transferred to start-ups for commercialisation. The technology is now sufficiently mature for offtake agreements to have been signed with large customers prepared to put capital at risk for multi-megawatt-scale projects, including Fervo and Google, Southern California Edison and Shell, as well as Sage and META in the United States, Google and Baseload Capital in Chinese Taipei, and Panasonic and Kyuden Mirai Energy in Japan. Commercial sources of capital have been providing more than USD 4 billion in debt and equity since 2022 for projects of nearly 1 GW scale currently under development.

Developers have reported significant progress in 2025, both for drilling cost reductions and for reaching hotter reservoirs. Concerted public R&D programmes and rising expectations for next-generation geothermal energy have the potential to create new avenues of innovation that could further reduce costs. This includes next-generation drilling (rotary-jet hybrids, non-contact/plasma approaches and automation), safer and better-understood stimulation techniques (soft stimulation and rigorous seismic mitigation), and high-temperature materials and sensors for supercritical systems.

Lithium-ion batteries

The initial research that paved the way for today's over USD 100 billion lithium-ion battery industry took place in publicly funded laboratories in the United States, Japan and Europe in the aftermath of the oil crisis. In the 1970s, all three were dependent on oil imports and searching for alternatives to reduce vulnerability to supply shocks.

In 1976, the United States passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Act, which supported some of the pioneering work on lithium-ion batteries. This helped spark some of the key advances over the following decade, including by Stanley Whittingham, who worked at Exxon, a

[23] See Geothermal Era-Net, followed by Geothermica, IMAGE, DEEPEGS, DESTRESS, Thermodrill, DESCRAMBLE, ORCHYD, GEMex, HOCLOOP, GeoWell and GSEU.

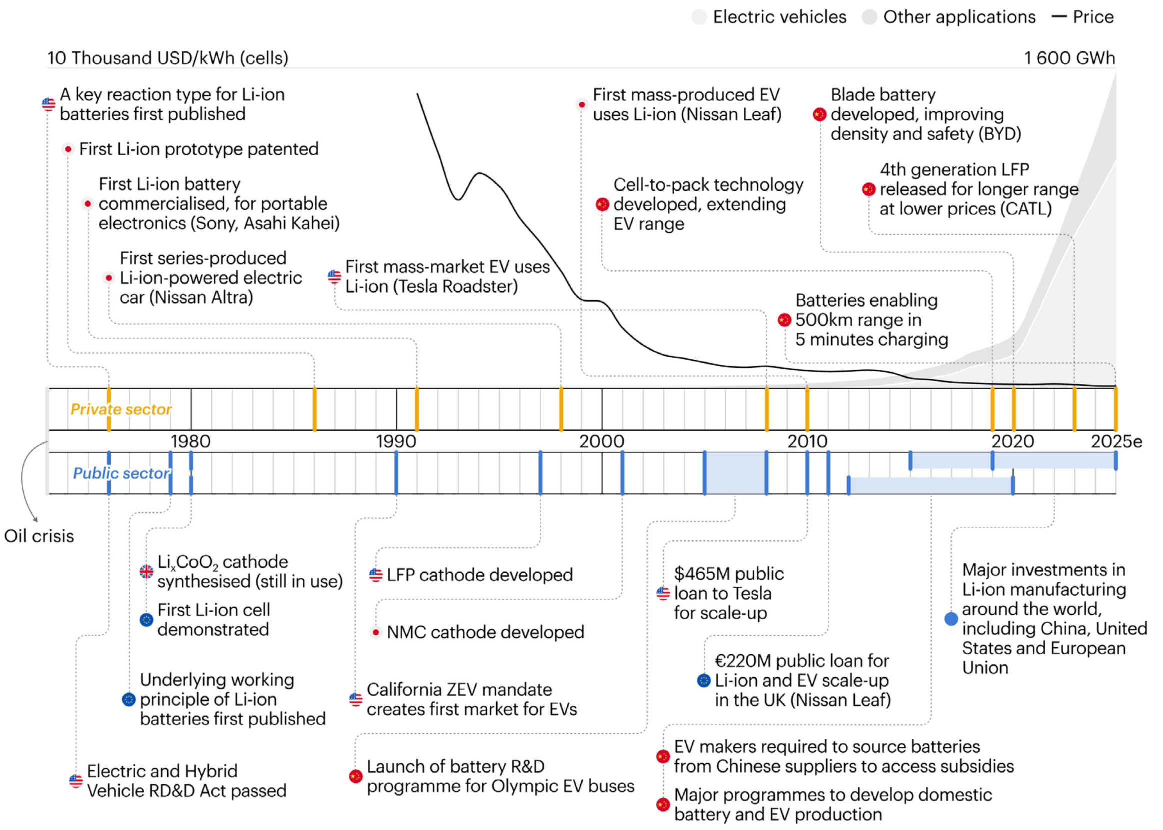
private US oil company. Whittingham's work was advanced by John Goodenough, a university researcher funded by US and UK public grants and whose first lithium-ion patent in 1980 was funded by a UK government energy research institute. Around the same time, Bruno Scrosati – a researcher at a publicly funded Italian university – built the first lithium-ion battery prototype, based on a principle proposed by Michel Armand while working for a French public research institute. Building on these developments, in 1986, Akira Yoshino, at private Japanese company Asahi Kasei, became the first patentor of a lithium-ion prototype. In 1991, Sony and Asahi Kasei first brought lithium-ion batteries to the portable electronics market, which requires energy-dense rechargeable batteries. Whittingham, Goodenough and Yoshino shared the 2019 Nobel Prize in Chemistry for their work, and Goodenough later cited the oil crisis and the variability of renewables as the original drivers for the R&D efforts.

It was not until the mid-2010s that electric vehicles (EVs) took over from portable electronics as the dominant driver of lithium-ion market demand. EV batteries represented less than 2% of lithium-ion battery demand in 2010, 40% in 2015, more than 60% in 2020, and over 70% today. During the same period (2010-2025), yearly battery deployment grew more than sixty-fold. Deployment was boosted from government grants for EV purchases in many countries over the same period. However, this followed more than two decades of R&D into the potential for lithium-ion in EVs. As far back as 1990, the first government-backed market demand initiative for EVs – California's Zero-Emission Vehicle Program in the United States – was established to reduce air pollution and targeted 2% of car sales having electric drivetrains by 1998. The first commercially produced EV powered by lithium-ion batteries was the Nissan Altra car, launched in 1998, which followed protype-level production of the Nissan Prairie Joy in 1996. The first serial-produced model, the Tesla Roadster, was launched in 2008. The Nissan Leaf was first produced in 2010 and became the first EV to exceed 100 000 units sold. Nissan received a EUR 220 million public loan from the European Investment Bank in 2011 for its European lithium-ion and Leaf manufacturing operations.

At around the same time, Chinese government support initiated a lithium-ion programme that has helped it become the world's largest manufacturer and market in subsequent years. A notable early milestone was the production of 50 electric buses with Chinese-made lithium-ion batteries for the 2008 Beijing Olympics, at a time when Japanese firms dominated the industry. In 2009, China's government launched the Ten Cities, A Thousand Vehicles programme, driving battery demand through large-scale public transport electrification. Policy support was further strengthened between 2012 and 2020. Starting in 2013, EV grants were extended to individual consumers and from 2015 (until 2019) they were only available for sales of EVs equipped with batteries from approved suppliers, all of which were Chinese. This mandate significantly boosted China's domestic industry at a time when these suppliers were small compared with Japanese and

Korean lithium-ion manufacturers – Samsung, a Korean company, had overtaken Panasonic, a Japanese company, as the world's largest producer in 2011. It also needed to be bankrolled to a high degree with public money: in 2014 alone, China's central and regional governments spent the equivalent of roughly USD 1.6 billion on subsidies. In addition, public funds have supported lithium-ion R&D in China, helping manufacturers to extend their competitive advantages. Today China is a world leader in battery innovation and Chinese companies such as CATL and BYD are at the forefront of the next frontiers, such as sodium-ion and solid-state batteries.

Global deployment, price and key milestones for lithium-ion batteries, 1973-2025



IEA. CC BY 4.0

Notes: Other applications refer to battery energy storage systems, portable electronics, electric bikes, hoverboards and drones, among others. Prices are reported in in real 2025 US dollars.

Sources: IEA analysis based on data from IEA (2025) Global EV Outlook; IEA (2025) World Energy Outlook; Avicenne Energy; CRU; Ziegler and Trancik (2021) Re-examining rates of lithium-ion battery technology improvement and cost decline; and BNEF.

Falling costs and higher deployment have helped establish new policy and market dynamics related to new supply chains and applications. From 2010, lithium-ion chemistry, design, and manufacturing were increasingly optimised for EVs, and global battery cell prices fell by over 40% by 2015 and 75% by 2020 compared with the 2010 level, as production expanded rapidly. This trend has continued as global sales expanded almost six times from 2020 to reach more than 17 million electric cars sold in 2024. With abundant supply and lower costs of lithium-ion batteries, governments have been able to encourage their use in stationary storage, in utility-scale plants and smaller ones in buildings, with yearly deployment growing more than twenty-fold in the past 5 years. Regulatory changes, falling prices and grants to installers are making lithium-ion batteries a critical component of modern power grids and other key infrastructures, such as data centres. Defence uses like drones and humanoid robots are emerging as strategic new markets, despite being expected to remain significantly lower in volume than the market for EVs.

To help ensure access to batteries, the jobs they create and their critical mineral inputs, governments around the world, notably in the United States and Europe, have made public capital available to cover risks associated with investment in domestic lithium-ion production. These risks arise from higher costs than those in China and inexperience with cutting-edge battery production at scale. Governments have also used policy tools to attract investments from overseas, from leading manufacturers headquartered in China, Korea and Japan.

Grid-forming inverters

As electricity networks become more reliant on power supplies that do not need rotating generators, such as turbines, to convert energy inputs into electricity, new means of stabilising grid frequency and voltage are required (Chapter 6). Grid-forming inverters are one of the most promising candidates to help maintain stability across the grid by demonstrating advanced control capabilities. There is not yet a major international market for these products, partly due to conservative investment policies of grid operators and partly due to limited experience outside pilot projects. However, they are being tested and deployed on electricity networks around the world and expectations are high. In 2018, a grid-forming inverter system paired with a 30 MW battery was installed in Australia and has performed as expected during potentially destabilising events. Several companies now market such systems.[24]

The market for grid-forming inverters has emerged only recently in response to a technical challenge that threatens the stability of power grids around the world. The commercial availability of these products to meet this need represents very good fortune for grid operators. However, it would be a mistake to attribute this to the foresight of corporate innovation. The story of grid-forming inverters begins in the 1990s, long before concerns about high shares of renewable electricity

[24] Siemens, ABB/Hitachi Energy, SMA, Huawei, Sungrow, FIMER and Tesla with Neoen.

generators were commonplace, with far-sighted research that was led by governments until relatively recently.

Inverters – a means of converting direct current to alternating current (AC), which is used to connect the direct current input from solar PV and batteries to the AC grid – were first patented in the 1960s, and used by the US National Aeronautics and Space Administration (NASA) for space applications. Yet the idea of an inverter that can use software to set its own voltage level in response to grid fluctuations only arose in the 1990s. In Chinese Taipei, researchers at the state-owned university and state-owned power company published evidence that digitally controlled inverters could reliably drive large synchronous machines, as used in a pumped storage power plant. In 1997 and 1998, University of Wisconsin-Madison researchers with a US National Science Foundation grant published the theory behind parallel-connected inverters and microgrid control. In 2001, researchers at one of Germany's national research institutes provided the proof of concept for the grid-compatible operation of parallel inverters, paving the way for the virtual-inertia and microgrid concepts that followed.

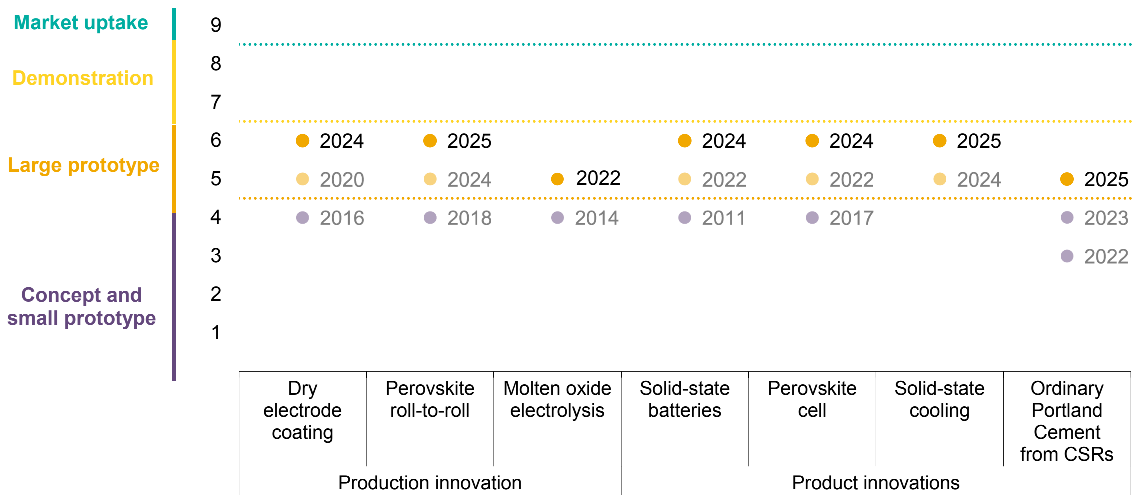
Progress quickened after the government-owned utility Hydro-Québec in Canada mandated frequency control for asynchronous generation in 2006, a requirement that created demand for devices that could emulate synthetic inertia for wind farms. However, corporate interest was still mostly confined to participation in publicly funded trials. These trials included the US National Renewable Energy Laboratory's Distributed Utility Integration Test, which started in 2006 with participation from the manufacturers SMA and Xantrex, which did not at the time offer grid-forming inverters. SMA is now a supplier of grid-forming inverter technology, while Xantrex was acquired in 2008 by French equipment maker Schneider Electric, which sells its grid-forming inverters. In 2011, researchers in the United Kingdom and Israel, with funding from the UK government, published a concept for a type of grid-forming inverter that can mimic synchronous generators. This led to Synvertec being founded as a company in 2014 to commercialise the product. In 2007 and 2016, the European Commission funded research projects on virtual synchronous machines and smart synchronous inverters involving small inverter companies such as Q3 Energie and Solutronic Energy. In 2020, the US government published a Research Roadmap on Grid-Forming Inverters, which confirmed the consensus that grid-forming inverters could play a large role in future system operation, but major manufacturers were still not marketing them.

It is only since 2020 that major manufacturers have brought grid-forming inverter products onto the market. They steadily began to integrate features such as black-start and inertia emulation into products from 2018 and large battery storage projects have since been equipped with grid-forming capabilities in several countries. In 2024, equipment suppliers and European transmission system operators (TSOs) jointly proposed a set of functional requirements for high-voltage direct current (HVDC) converters to also start incorporating grid-forming capabilities. In tandem, some regulated grid operators have adapted their rules to require inertia emulation. To bring down costs and increase the value of grid-forming inverters, further innovation by researchers and manufacturers is needed to improve large-scale controller interactions, harmonics, and transient stability in low-inertia systems. However, the next stage is most dependent on the creation of a sustainable market that incentivises learning and cost reductions, for example through appropriate regulation alongside battery deployment.

Opportunities for innovation to boost competitiveness in key technology areas

Innovation can reshape the competitive landscape for a given technology in three main ways: by lowering manufacturing costs; enabling designs with superior performance compared to existing options; and creating products that combine improved performance with manufacturing processes that rely on cheaper inputs. Several emerging technologies in manufacturing and product design have recently reached the demonstration phase and could soon be commercialised on a large scale, including dry electrode coating, roll-to-roll perovskite production, solid-state batteries and solid-state cooling.

Technology readiness level timeline for selected emerging clean energy technologies and production processes



Notes: CSRs = calcium silicate rocks (e.g. basalt). Solid-state cooling uses caloric effects in solid materials (e.g. baro-, magneto-, elasto- and electro-caloric) instead of vapour compression refrigeration.

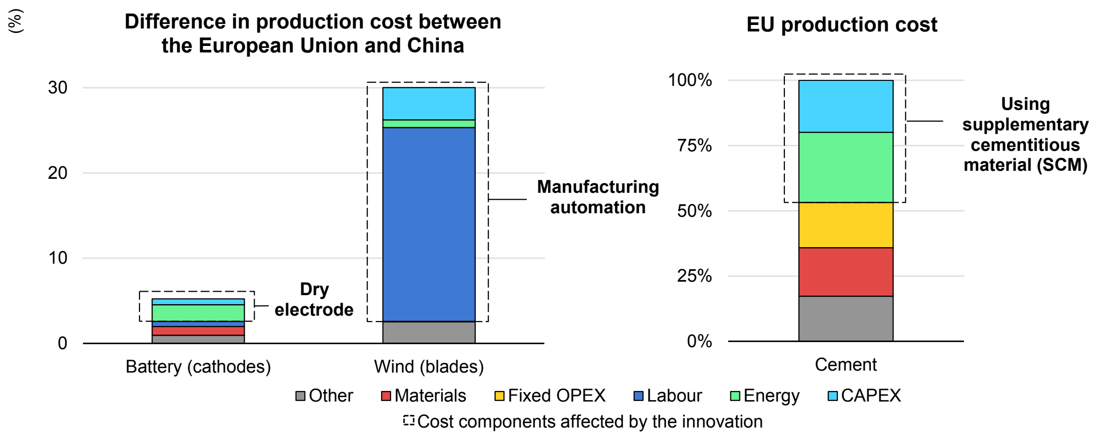
Countries and regions that pioneer new technologies are not always the ones that ultimately capture the industrial benefits. Solar PV and lithium-ion batteries are well-known examples: while much of the early research and pre-commercial development took place in the United States, Germany and Japan, the dominant industrial base has since consolidated in China. This highlights the importance for governments of creating conditions that allow innovations developed in domestic laboratories and start-ups to translate into local manufacturing activity, in order to capture the full economic and strategic value.

Improving manufacturing processes to cut costs

Manufacturing costs can be reduced through process innovations that improve efficiency – for instance by increasing accuracy or speed, lowering energy or labour intensity, or cutting capital expenditure needs. For example, silicon carbide wire sawing of silicon ingots into wafers was developed in the 1980s for semiconductors and solar PV, reducing silicon waste and cutting costs by around 17%.

Innovations that reduce labour, energy use and capital expenditure are especially relevant for narrowing manufacturing cost gaps between China and advanced economies. They could help advanced economies strengthen their position in global clean energy supply chains, including, in some cases, by also improving product quality. Dry electrode coating for batteries, manufacturing automation for wind turbines and supplementary cementitious materials fall into this category.

Examples of emerging technologies that could address clean energy cost gaps



Notes: CAPEX = capital expenditure; OPEX = operational expenditure. Production cost refers to the levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Costs shown here are exclusive of explicit financial support but may include financial support embedded in individual cost components (e.g. fossil fuel subsidies).
Sources: IEA analysis based on data from IEA (2024), Energy Technology Perspectives 2024.

- **Dry electrode coating** is an emerging, not yet commercial, technology that eliminates solvents and the energy intensive drying stage in battery cell manufacturing. It could reduce energy use in the coating step by up to 20% and lower total cell manufacturing costs by around 5% when savings in capital expenditure and labour are included. Its impact is promising, as manufacturing innovation alongside economies of scale drove the 75% fall in lithium-ion battery prices between 2015 and 2024.

- In wind power manufacturing, **robots that automate layering, trimming and finishing** could reduce labour needs significantly. Labour accounts for around 25% of the levelised cost of producing wind turbine blades in advanced economies. Automation of the finishing steps alone could potentially cut costs by up to 60%. Automation is also advancing in labour-intensive nacelle assembly: machines capable of handling heavy loads and applying high torque are being developed. In wind tower fabrication, spiral welding could integrate rolling and welding into a single continuous operation.
- Substituting clinker in cement production with **supplementary cementitious materials** is an innovation that can reduce the overall capital and energy intensity of cement facilities. These materials can be by-products from other industries – such as fly ash, silica fumes or blast furnace slag – or materials produced separately, such as calcined clays. Co-production of multiple outputs within one integrated facility could be another means of reducing overall capital intensity and may significantly enhance project revenues. Brimstone, a US start-up, is building a facility to co-produce cement and smelter grade alumina without using limestone, which is a main source of CO_2 emissions from cement production.

The potential of artificial intelligence innovation to transform manufacturing

The application of AI to industrial processes is a fast-moving field. A range of AI techniques are being applied to improve accuracy, speed, fault detection or cut unit costs. The IEA Energy and AI Observatory provides examples and insights into the implications of AI applications for efficiency, innovation, resilience and competitiveness in the energy sector. It includes several examples related to industrial processes and manufacturing.

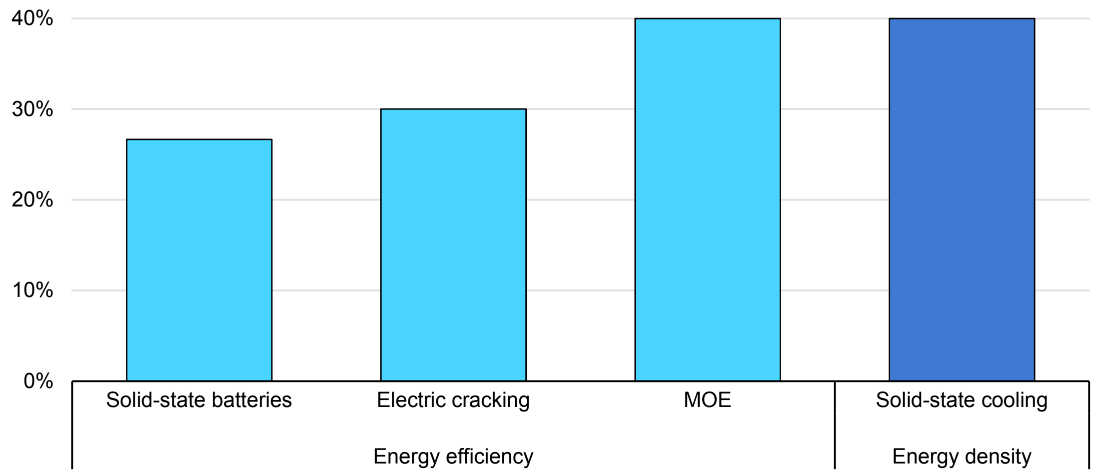
- In 2024, at Heidelberg Materials' Mokra cement plant, Carbon Re implemented AI models for real-time clinker quality predictions and oxygen target recommendations, integrated with closed-loop control. The goal of the project was to reduce fuel costs, lower carbon emissions and improve clinker quality. Through a one-month-on, one-month-off test period, the AI intervention achieved a 4.1% reduction in the fuel cost index, a reduction of 4.5 kg CO_2/tonne of clinker (approximately 2%) and a 1.8% increase in alternative fuel use.
- Fero Labs' machine learning software uses causal inference and generative AI to optimise ferroalloy additions during the refining stage of a steelmaking operation, contributing to more efficient and cost-effective scrap usage in steel production. It is currently deployed across several electric arc furnace mills in North America, and one of these mills used the software to achieve a 3.3% reduction in global warming potential.

In a further example, by analysing manufacturing processes in real time with AI, Panasonic has shown it can effectively improve production yields and strengthen quality control, ultimately reducing manufacturing costs while increasing quality. At the same time, AI can be used to anticipate needs for production equipment maintenance, helping to reduce production line downtimes. This approach is also being adopted by other leading battery manufacturers, such as CATL.

Developing new technologies with better performance

New designs and technologies with superior performance can open markets and create a first-mover advantage for the countries that develop them, on condition they are supported by intellectual property rights protection, the availability of a local expertise and the development of a robust industrial ecosystem and supply chains. In addition to direct cost comparisons, superior performance can relate to a variety of criteria that are important to customers, including convenience, additional features, environmental performance, compliance with forthcoming regulations, and speed of deployment. Solid-state cooling, electric cracking of hydrocarbons, electrolysis of steel and solid-state batteries fall into this category.

Maximum potential efficiency and performance improvements of emerging technologies relative to today's conventional benchmarks



Notes: MOE = Molten Oxide Electrolysis for steel production. Each innovation is benchmarked against today's mainstream technologies: Solid-state cooling is compared with the global average efficiency of air conditioners currently sold; Electric cracking is assessed relative to the energy efficiency of conventional steam-cracking; Solid-state batteries are benchmarked against the energy density of current lithium-ion nickel manganese cobalt (NMC) cathode batteries at the system level; MOE is evaluated against the energy demand of a blast furnace (however, this value reflects a theoretical lower bound, and current laboratory MOE systems operate well above this level once overpotentials, heat losses and balance-of-plant requirements are included).

Sources: IEA analysis based on Allanore, Ortiz and Sadoway (2011), Energy Technology 2011: Carbon Dioxide and Other Greenhouse Gas Reduction Metallurgy and Waste Heat Recovery); IEA (2025), How can innovation help secure future battery markets and mineral supplies? and Toribio-Ramirez (2025), Cost reduction analysis for sustainable ethylene production technologies.

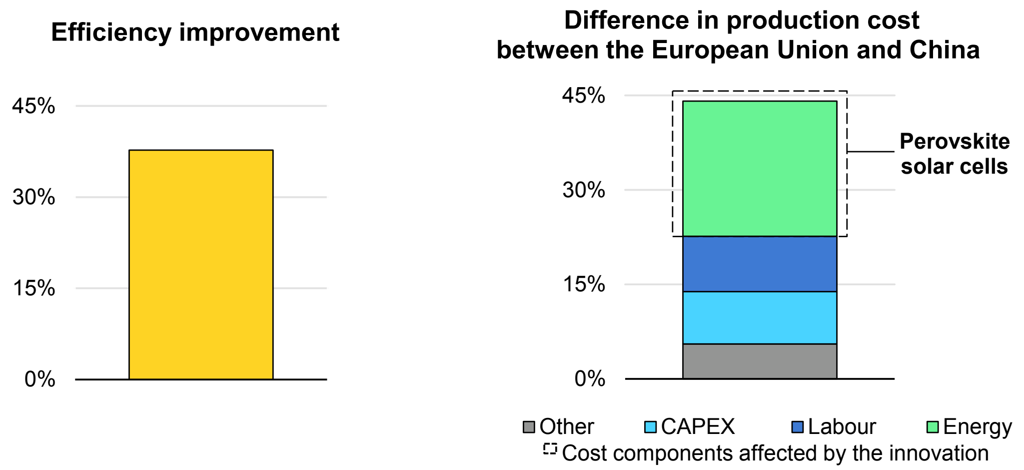
- **Solid-state cooling** for air conditioning and other applications has already reached efficiency levels comparable to vapour compression systems, with the potential to match best-in-class performance in equipment based on the vapour compression cycle. It relies on different physical principles, components and materials to today's market leaders and successful commercialisation could provide first-mover advantages.
- In heavy industries, steam-cracking (a high-temperature process) has been the main way to split ethane, liquefied petroleum gas and naphtha into smaller carbon chains since its development and commercialisation in the 1940s. Switching from fuel combustion to **electric cracking**, which is more efficient for heating, could in some cases reduce energy intensity by over 30%. Once demonstrated at scale, it could be cost competitive in places with high fuel costs and access to low-price electricity. In 2024, a 6 MW demonstration plant started in Germany.
- **Molten oxide electrolysis** would be a simpler way to make primary steel than the dominant multi-stage blast furnace and basic oxygen furnace method. This method decomposes metal oxides such as iron ore into liquid metal and oxygen using electricity alone. Originally developed in the mid-2000s as a means of obtaining oxygen from iron ore in space by researchers at NASA and MIT, a private US university, it is now being developed for steel and critical minerals by start-ups such as Boston Metal. By eliminating intermediate steps such as coking, sintering, and reduction, it could theoretically be 25-40% more efficient than carbon-based processes. It may also allow avoidance of other energy intensive steps related to preparing iron ore, and could be operated flexibly in response to electricity grid needs. Commercial-scale demonstration will be needed to prove that electrodes can withstand molten electrolytes at 1 600°C and to list it above TRL 5. However, a path to market supported by revenues from critical mineral co-products is taking shape via recent pilot projects.
- **Solid-state batteries** have higher energy density and improved safety compared with today's lithium-ion batteries.[25] They could significantly extend the driving range of EVs and ease the electrification of long-distance heavy-duty transport. BYD, a Chinese company, aims to launch its first EV with solid-state batteries in 2027 and scale up to mass production by 2030. Toyota, a Japanese company, and Samsung, a Korean company, are targeting similar timelines. While direct competition with lithium-ion batteries remains some years away, due to immature processes and supply chains, premium markets where range and lightweight performance are valued could support early adoption. Such applications promise new entrants a protected space for learning and cost reduction, but it requires overcoming cell manufacturing and battery pack integration challenges.

[25] Solid-state batteries refers here to all-solid-state batteries, which are not yet commercialised. Semi-solid-state batteries (first commercialised several years ago) and quasi-solid-state batteries are steps on the way to realising the full potential.

Developing new technologies that offer both advantages

Some technological innovations enhance competitiveness by simultaneously improving performance and avoiding costly inputs. In addition, to offering a first-mover advantage to firms in countries where they are developed, they can also let these countries reduce dependence on concentrated supply chains. Perovskite solar cells are one example.

Performance improvement and components of the cost gaps that could be addressed with perovskite solar cells



Notes: CAPEX = capital expenditure. Difference in production cost is reported for an integrated solar value chain. Perovskite-silicon tandem solar cells currently demonstrate power-conversion efficiencies of around 31-32%, compared with typical commercial crystalline-silicon modules in the 22-23% range.

Sources: IEA analysis based on Kavlak et al. (2018), Evaluating the causes of cost reduction in photovoltaic modules; Fraunhofer ISE (2025), Scalable Perovskite Silicon Solar Cell with 31.6 Percent Efficiency Developed; Yan et. al. (2019), A review on the crystalline silicon bottom cell for monolithic perovskite/silicon tandem solar cells.

Instead of using silicon wafers, **perovskite cells** rely on light-absorbing materials with a perovskite crystal structure. These can be processed into ultra-thin films with theoretical efficiencies comparable to silicon. More importantly, they enable much higher efficiencies because they can be combined in so-called tandem cells with silicon or other perovskites that absorb light of different wavelengths. In addition, their extremely thin structure and very high light absorption enable them to generate power in low-radiation conditions, such as indoors or on cloudy days.

Perovskite cells need fewer material inputs and can be manufactured at lower temperatures than silicon cells. Lower temperatures reduce energy needs and allow electricity-based techniques to economically replace the fossil fuel needs of polysilicon refining and wafer manufacturing for today’s market-leading solar cells. As energy costs account for roughly half of the cost gap between China and most advanced economies, perovskites could be more competitive in advanced economies if they can be successfully scaled up. The most common high-performance perovskite cells rely on iodine, whose primary global production is concentrated in Chile and Japan.

China, Europe and Japan are leading centres of perovskite R&D today, with a significant focus on manufacturing processes (because the production methods differ so radically from those of conventional silicon cells) and on materials science for durability. One promising manufacturing technology to enable continuous operations is roll-to-roll production, similar in principle to newspaper printing. In 2025, this complex and multilayer approach reached the demonstration phase under real operating conditions.

Knowledge gaps and priorities

The link between innovation and competitiveness is well established – as evidenced by the winners of the 2025 Nobel Prize in Economics – but it is not straightforward to translate this into energy sector evidence and policy guidance. This chapter reviews a range of studies that find that government support to energy R&D generates benefits to the economy that outweigh the costs, typically by 3-to-1 and often much higher. It also shows the ways in which public support was instrumental to success in four specific and different cases of energy technology development that are now attracting significant amounts of capital. Finally, it highlights targeted ways in which technology innovation could raise the competitiveness of domestic energy technology manufacturing or use in countries that currently face higher energy and other input costs. Finally, it highlights targeted ways in which technology innovation could raise competitiveness of domestic energy technology manufacturing or use in countries that currently face higher energy and other input costs.

Taken together, the assembled insights point towards several knowledge gaps that currently leave governments under-equipped to take key policy decisions, and to decide on priority actions to spur greater competitiveness for domestic facilities.

- **Knowledge gap: comparable policy evaluations**. Policy makers need robust information about the impacts of different policy types and the economic value of supporting energy innovation. At present, few governments undertake rigorous assessments of the added value generated by recipients of their support and, ideally, non-recipients too. This puts research funders in a weak position when justifying budget increases or making the case for why energy innovation should be among the last budgets to be cut in straightened times, not one of the first. As first steps, evaluators can share knowledge on effective metrics and methods, including starting to build datasets of relevant information from the very beginning of new programmes to 5-10 years after their conclusion. Modelling impact expectations beforehand provides a basis for evaluation after the event.

- **Knowledge gap: value-chain ecosystem thinking**. Healthy innovation ecosystems are fundamental to success but also hard to define. The most effective innovation communities – whether centred on San Francisco, London or Singapore (see table) – have leading universities, technology-led corporations, access to public resources, networks of experts, and knowledgeable investors competing to back the next big thing. However, co-operation between them is still important: FLNG, geothermal, Li-ion batteries and grid-forming inverters did not emerge from a single ecosystem. Many evolve specialisations and attract businesses from upstream and downstream in the supply chain to collaborate at the technology frontier. For example, in 2025, German car company Volkswagen opened a new R&D centre in Hefei, a hub for battery manufacturing and digital technology. While companies usually keep R&D facilities in the country of their headquarters and founding, they often seek out the best innovation ecosystems for their value chain as they grow. There are currently only limited analyses and discussions about how to foster industrial and innovation activity around strategic value chains for domestic competitiveness.

Top two cities in North America, Europe and Asia by number of active energy start-ups

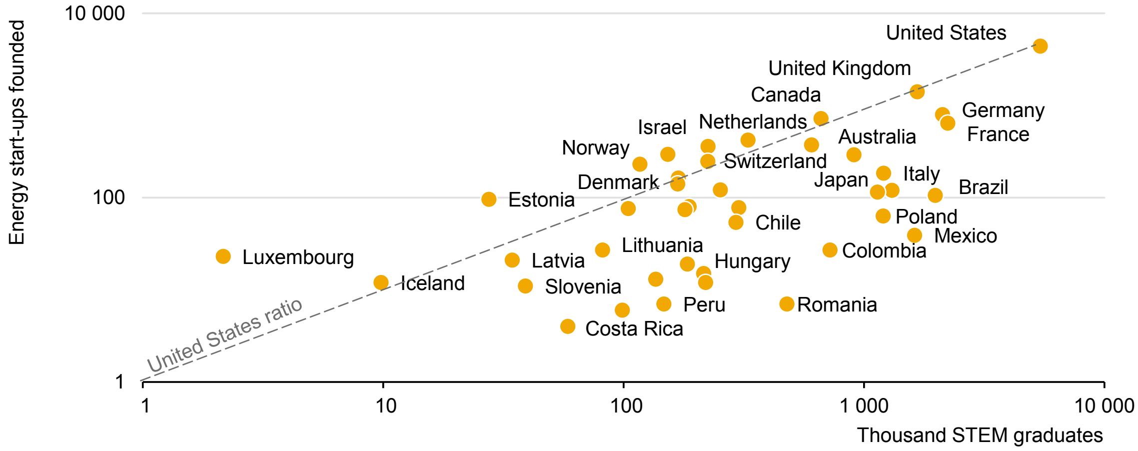
City	Active energy start-ups	Energy VC funding (USD billion [2025])	Areas of specialisation	Universities and research centres	Global (non-energy) innovation rank
North America					
San Francisco (United States)	229	20.9	Batteries and EVs, aviation, critical minerals	UC Berkeley; Stanford University; Lawrence Berkeley National Lab	3
New York (United States)	104	7.2	EVs, solar, electricity grids, critical minerals, energy efficiency	Columbia University; New York University; CUNY Energy Institute; Syracuse Center of Excellence	7
Europe					
London (United Kingdom)	123	3.1	EV charging, CCUS, energy storage, hydrogen	Imperial College London; University College London; King's College London; Brunel University	8
Paris (France)	50	2.5	EV charging, nuclear, solar, bioenergy	Paris-Saclay University; CEA; IFP Energies Nouvelles	12
Asia					
Singapore	34	0.8	Chemicals, electricity grids, batteries	National University of Singapore; Nanyang Technological University; Agency for Science, Technology and Research	16
Shanghai (China)	25	4.3	Nuclear, hydrogen, aviation, batteries, EVs	Shanghai Jiao Tong University; Shanghai Advanced Research Institute	6

Notes: CCUS = carbon capture, utilisation and storage. Active energy start-ups based on deals done since 2020. Energy VC funding is the amount raised by start-ups in the city since 2020. Start-up allocation to cities uses a 100 km radius from firm headquarters. Global innovation ranks taken from the World Intellectual Property Organization (WIPO) Global Innovation Index.

Sources: IEA analysis based on data from Cleantech Group (2025), Crunchbase (2025), WIPO (2025), McKinsey (2025), Cleantech San Diego, Bpifrance (2025).

- **Priority: encourage entrepreneurship**. Economic competitiveness proceeds by displacement of old technologies with ones that can perform cheaper, faster and more sustainably, or do many more things at once. The big step from innovation outputs to impacts is via commercialisation of products and services, often by existing corporations with the capital resources to take on some of the risk. However, outsider start-ups play an increasingly important role in challenging the status quo and pushing incumbents to stay competitive. Despite this, not all innovation ecosystems incentivise innovators to take the risk of building a company to reshape the market and realise the full potential of their new energy technology. Unattractive fiscal regimes for entrepreneurs, a lack of intellectual property ownership, few mentors and unsympathetic financers are among the reasons why many places with strong scientific universities underperform in terms of energy start-up creation compared with the United States. Estonia, Luxembourg, Israel,[26] the Netherlands and Norway are among the few countries that have higher rates of energy start-up formation per science, technology engineering or mathematics graduate than the United States.

Energy start-ups founded and graduates in science, technology, engineering and mathematics fields, 2015-2023



Notes: STEM = science, technology engineering and mathematics. Log scale. Only bachelor and first-degree master's courses included. The dashed line represents the ratio observed for the United States, such that countries above the line have more founded energy start-ups in the period per thousand STEM graduates than the United States.
Sources: IEA analysis based on data from Cleantech Group (2025), Crunchbase (2025) and OECD (2025).

- **Priority: anticipate future needs and share the first-mover risks**. The opportunities for innovation to boost competitiveness summarised in this chapter indicate potential targets for R&D and co-operation. Governments and others who wish to exploit these opportunities can learn from the case studies. A common theme across FLNG, geothermal, Li-ion batteries and grid-forming inverters was the leadership shown by public agencies and risk-taking firms long before the market for the technology was assured. Not all of these case studies exhibit strategic foresight of government, but they all show the importance of commitment to the longer-term promise while allowing competition between different designs. In the case of FLNG, finance and offtake agreements for the first shipments was critical. For geothermal, open access test centres and data reduced barriers to

[26] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

entry. Grid-forming inverters were developed in partnership with the private sector only after far-sighted public researchers had recognised a potential future problem. They each show the ability of public-private partners to anticipate competitiveness opportunities proactively and take on different shares of the risk at different stages. There are parallels with countries working to create innovation ecosystems around AI and industry, without knowing the nature of the potential spillovers, as well as in other areas such as electrolysis and power transmission.

Chapter 6. Focus: Technology innovation for electricity grid resilience

Preventing disruptions and ensuring rapid restoration of power is a duty for electricity network operators, but serious new challenges require new approaches to the resilience of power grids. These challenges stem from a range of factors including age, weather and technological changes to how power is supplied and used. There are many opportunities for technology to help address these challenges, modernising grids and making them more flexible, if the funds required for investment can be mobilised.

This chapter introduces the challenges that grid operators are increasingly facing and describes in detail the various technologies that can address each major challenge. Some need further innovation but, in many cases, there are available and proven technologies whose early deployment is still slow in comparison to the expected needs in the next decade or more. Sluggish uptake – whether for institutional, market or financial reasons – is a problem: it stymies learning and cost reductions, and it can raise the cost of future interventions if today's emerging problems intensify over time. If grid innovation and deployment of new technologies fails to keep pace, countries risk falling short of the full economic and social benefits of changes in electricity supply and demand. Connection queues for new projects will be longer, existing infrastructure will be underutilised, exposure to service disruptions will rise and deployment of more flexible and renewable assets will hit unnecessary constraints.

The chapter highlights how network regulation does not always incentivise the trial and adoption of new technologies, and how a lack of co-ordination between networks – internationally, and between voltage levels – slows uptake further. It shows that ensuring future grid resilience is constrained less by the availability of technology than by the pace of integration of available technologies. Many appropriate technical products and services are already at high readiness levels and operating somewhere in a real-world system. However, bringing down costs and optimising the use of new equipment needs deployment, which relies on planning, regulatory incentives, market designs and accountability.

In light of this, the chapter closes with recommendations for innovation policy in this area, including system-level initiatives, real-world testing environments enabled by so-called regulatory sandboxes, and clear pathways to scale-up for suppliers. Governments can learn from each other's experiences with performance-based procurement of stability services, standardised equipment specifications and allocation of responsibilities between network operators and regulators. In parallel, continued R&D into the challenges that appear on the horizon for the medium-term must continue. Recent experience has taught grid operators the importance of continual modernisation of electricity networks.

The challenges faced by electricity grids today

Modern electricity systems are the largest machines operated in the world. Laid end to end, the world's power lines stretch more than halfway to the sun, more than 84 million kilometres. Synchronous interconnected grids involve thousands of power plants that must rotate at a constant frequency and balance supply and demand instantaneously. In Europe, the Continental Europe synchronous area, the world's largest by connected capacity, holds a constant frequency across 24 countries, serving over 400 million customers. In North America, the Eastern Interconnection maintains the same frequency from the Rocky Mountains to the Atlantic and from central Canada to Florida.

The interconnectedness of networks provides a range of benefits – including greater resilience – but can also be a vulnerability. In April 2025, a series of imbalances on the power grid cascaded into a widespread blackout across Spain and Portugal, stalling airports and rail, knocking out traffic light systems, mobile and internet service and payments, and disrupting the daily life of tens of millions. While this story made headlines, outages are not unknown, even in the most modern electricity systems. Notable outages also occurred in Chile in 2025, Texas in the United States in 2021, the United Kingdom in 2019 and South Australia in 2016. As energy systems are progressively reshaped by large-scale electrification and rapid growth in renewables, the ability of the grid to reliably cope with new technical challenges – through preventive measures and ensuring rapid recovery from events – is a question of energy security. As these challenges bear upon the electricity system as a whole, the solutions must also be evaluated system-wide, with a growing role for measures that ensure rapid recovery of the grid, as well as technologies to prevent cascading failures. In Spain and Portugal, supplies were restored relatively quickly due to the availability of modern communication and control technologies, and interconnection with France and Morocco.

Converging resilience challenges facing electricity grids

- **Rising and changing demand**. Electrification is advancing rapidly. In 2024, electricity demand growth rates nearly doubled around the world. With electric vehicles and heat pumps becoming mainstream, and the advent of a race to build data centre capacity, electricity demand in advanced economies is set to rise, after a decade of relative stagnation. This puts pressure on grid operators to increase the available capacity of cables, transformers and other equipment quickly in a context where permitting and construction in many regions is slow. Finding ways to make better use of existing infrastructure or avoiding infrastructure additions entirely has become a priority. Additionally, some of the growth in power demand has characteristics that can be potentially destabilising, unless mitigation measures are put in place. For example, electric vehicle charging can introduce deviations from the standard waveform governing grid frequency, and data centres can have unpredictable swings in power consumption.
- **Changing geography of electricity supply and demand**. Growth in electricity supplied from solar PV and wind was equivalent to 70% of the growth in all electricity supply in 2025, and its share of generation has nearly doubled since 2020 to 17%. These sources are typically further from existing centres of demand and are more geographically dispersed. Supplies are increasingly connected to the distribution grid, which did not traditionally need to manage power generators and also has to cope with the connection of more variable sources of demand and internet-enabled devices. Data centres are also being located in places that are not previous industrial sites, requiring new grid reinforcements that can be bottlenecks to investment. These developments potentially raise the cost of connecting each additional megawatt of supply and demand unless more efficient types of conductors and more local use of supplies can be used. An estimated 2 000 GW of renewable projects in advanced stages of development are currently waiting for grid connection globally.
- **Rising variability of supply and demand**. Variable sources of generation, like solar and wind, cause larger fluctuations in power flows. Unlike sources that rely on thermal or hydraulic turbines (like nuclear, gas, coal, hydro or biomass plants), they do not have large rotating generators that help keep grid frequency stable. In parallel, some new sources of rising power demand, including electric vehicle charging, do not follow traditional daily peaks and lows. Without specific measures, variability makes it harder to maintain stable frequency and voltage, potentially increasing blackout risks.
- **More cyber-attacks**. A network with more digital control is more efficient and responsive, but can also be more vulnerable. While they have not yet caused a large-scale blackout, cyber-attacks on energy and utilities globally jumped 42%

in a single year between 2023 and 2024, while regulators estimate the number of vulnerable points in US power grids is growing by around 60 per day and is now above 24 000.

- **Higher frequency and intensity of extreme weather**. Much of the world's transmission systems are above ground and exposed to storms, wildfire and extreme weather events, which were not as numerous or severe at the time of their construction. Taking the United States as one example, 80% of large outages from 2000-2023 were weather-related, and the number of weather-related outages in 2014-2023 was about twice that in 2000-2009. Europe's transmission system operators now rank extreme weather as a more severe threat to the power system than cyber-attacks. In the United Kingdom, two major storms in the 2021-2022 season left 2.7 million customers without electricity, and California's 2025 fire season forced over 20 power shut-offs to protect equipment.
- **Ageing infrastructure in advanced economies.** Over half of grid infrastructure in advanced economies is now more than 20 years old, and many components have already exceeded their 30 or 40 year design lifetimes. Ageing components pose safety and reliability risks. Delays in replacements over recent decades have led to bottlenecks, as grid owners have moved in tandem as weaknesses have become more acute with the demand of electrification. This is one reason why procurement costs for essential grid equipment almost doubled in the last 5 years.
- **Lagging progress towards electrification in emerging and developing economies**. In these countries, many grid operators have struggled to finance grid expansions that can keep pace with rising demand for electricity, leading to frequent disconnections when systems are under stress. In sub-Saharan Africa, over 600 million people still lack electricity access, and a cross-country analysis for the region estimates that power outages cost economies about 2.1% of GDP on average, with firms' sales around 5% lower than they would be with reliable electricity. At the same time, according to the World Bank only two countries in the region have power sectors that fully cover their costs, limiting their ability to invest in grid expansion, modernisation and new technologies. As a growing share of demand turns to electricity and more consumers and communities adopt solar PV and batteries to meet their electricity needs, the lack of available, affordable and capable technologies to integrate these resources into the grid makes it harder to operate a stable, secure system.

The timelines for technology innovation for electricity networks are typically slower and have different characteristics than other parts of the energy system. The sector is dominated by highly regulated companies with a legal mandate to minimise risks, known as Transmission System Operators (TSO) and Distribution

System Operators (DSO). The mandates of TSOs and DSOs have traditionally been based on centralised grid models, that now need to be updated so that DSOs – which are much more numerous – share responsibility for system-level stability with more generators connected to the distribution grid. However, the rules for grid investment and operations evolve only slowly and with strong government involvement. These rules sometimes do not even provide a mandate to tackle emerging grid challenges, instead focusing mostly on serving existing patterns of demand. In some cases, regulations can even incentivise operators to maximise spending rather than optimise efficiency and performance at lowest cost. Innovation is also slowed by long asset lifetimes: grid equipment is designed to operate for decades, making early replacement difficult to justify even when better solutions exist. In addition, because networks are often in populated areas or across land governed by multiple authorities, permitting and approvals can be prolonged, particularly for technologies that are unfamiliar to regulators. Authorities proceed with caution, triggering repeated reviews and verifications.

As a result, the primary customers of new electricity grid technologies have low incentives to adopt them and, when they do engage in field trials, these can be slow and raise the risks for innovators seeking to invest in scale up. A further complication is that TSOs and DSOs often follow fixed regulatory cycles of 5 to 10 years for investment and, if a technology is not validated and approved in time for the next investment cycle, this can lead to lost opportunities for technological change. Start-ups frequently need to partner with large equipment suppliers with the balance sheets and manufacturing capabilities to manage these risks, or to be acquired by them.

Many governments are aware of this dilemma between risk mitigation and the inherent risks of innovation. Policy tools such as pro-innovation regulatory models[27] and regulatory sandboxes have been introduced to support more experimentation and faster adoption of high potential emerging technologies – instead of having network operators that continue to commit to tried-and-tested equipment at higher costs or with longer construction delays than necessary. These are positive developments, and governments can learn from the early experiences of other countries and regions in this regard.[28]

Some grid-related technologies are not owned and operated by electricity system operators. As a result, they can often find a faster path to market when electricity markets incentivise early-adopters in the private sector. They include demand-side flexibility resources such as batteries or virtual power plants. Countries that have already achieved high levels of variable renewable power generation,

[27] For example, the UK RIIO model (revenue = incentives + innovation + outputs).

[28] A recent example of regulation-led innovation for grid technologies is the scheduled ban on sulphur hexafluoride use in switchgear. Legislated in 2024, the ban comes into effect for new medium-voltage equipment in 2026, with a timeline for other voltages up to 2035. It has spurred commercialisation and cost reduction for less polluting alternatives.

demonstrating that these sources can be introduced without a loss in reliability, have encouraged innovation by market participants, as well as by TSOs and DSOs, which have made major improvements to their grid control technologies. Denmark, Germany, Greece, Ireland, Portugal and Spain have achieved shares of 40% or more of solar PV and wind in their electricity mix without decreasing the availability of electricity to customers. South Australia's grid averaged 74% in 2024.

The case for strengthened innovation

Technologies that can address electricity grid challenges can be grouped according to their maturity and availability. In the area of technologies for assuring electricity grid resilience, there is a range of options across all categories of grid equipment that are already technically proven but face cost, performance and regulatory barriers to their adoption. At present, there is a smaller number of early-stage low- technology readiness level (TRL) technologies that are highlighted in this chapter for their high potential contribution and the importance of optimising them for market deployment. With further adaptation, these could potentially be successfully transformed into improved products. However, with the exception of certain proposals for long-duration energy storage (LDES) in novel batteries or thermal or mechanical processes, there are very few entirely new classes of technology at low TRL for which there are still high uncertainties about capabilities.

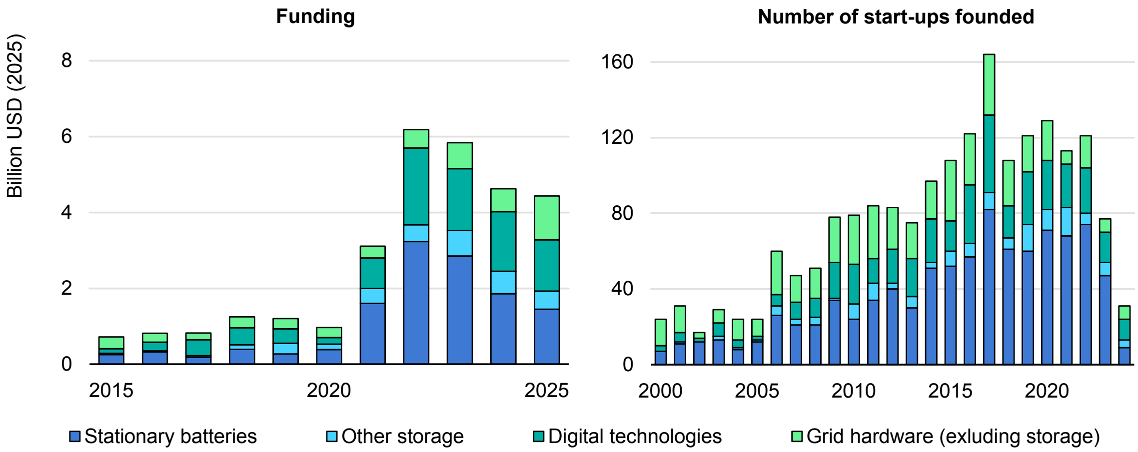
Three categories of technology availability for electricity grid resilience

Technology availability	Description	Examples
Mainstream, but still not used on many grids	Commercial and trusted technologies at TRL 9 that have been developed and deployed in recent decades to expand grid capacity and ensure resilience. They are not yet universally used and have potential for further cost reductions and adaptation to new contexts.	High voltage direct current (HVDC) systems; static compensators and frequency converters; renewables forecasting tools; synchronous condensers; large-scale stationary batteries; telecommunications for enhanced monitoring and control at the edges of the grid.
Available to the market for the past decade but uptake remains low	Technologies that are on the market and have been proven to be effective in commercial conditions, but remain at an early stage of deployment due to costs and the lack of incentives for grid operators to invest in them.	Grid-forming inverters; distributed resource energy management system (DERMS); virtual power plants (VPP); dynamic line rating (DLR); grid digital twins.
Pre-commercial but close to TRL 9	Technologies that have recently been developed to tackle arising grid challenges more effectively and which are currently being tested in their first pilot projects and field trials.	Long-duration energy storage (excluding pumped hydro and compressed air); E-STATCOMs; high-temperature superconducting cables, smart transformers; artificial intelligence (AI)-powered grid health monitoring and forecasting; multi-terminal HVDC networks.

The availability of many technologies at TRL 9 does not mean that technology innovation is not important. A key aspect is that, for electricity grids, their optimisation for system-wide co-ordination and value is what matters, not just their individual maturity. In addition, innovation during the early phases of deployment is still intensive, and many start-ups get founded and raise funding to try to gain market share. There has been a wave of new grid technology start-ups founded in recent years, with around 120 created each year since 2016 by entrepreneurs with new inventions or technical services. Many of these have been in the area of energy storage, with battery developers in particular helping to push venture capital fundraising for grid-technologies to USD 6 billion in 2022. Despite a decline in funding since then, grid-related venture capital has been more resilient to the wider downturn in venture capital investment than other areas of energy technology, indicating that investors see it is an area with dependable growth potential (see Chapter 2).

Commercialising a high-TRL technology involves different types of technology innovation: improvements to manufacturing, competition among suppliers with alternative designs and learning-by-doing, and it results in reduced costs and better product offerings. This process cannot happen without supportive markets, investors, standards and business models. In the case of electricity grid technologies, regulation and alignment between TSOs and DSOs in different regions is a major factor.

Venture capital fundraising by grid technology start-ups, and numbers founded, 2010-2025



Notes: Numbers of start-ups founded in 2024 and 2025 are underestimates as many start-ups only become publicly known once they have existed for 2 or more years and raised initial funds. For battery-related funding amounts, only budgets estimated to be allocated to stationary storage applications are included, but for the estimation of the number of start-ups, more battery start-ups are considered (including start-ups with intellectual property related to electric vehicle batteries).
Sources: IEA analysis based on Cleantech Group (2025) and Crunchbase (2025).

In the following sections, an overview of the technology landscape is provided to identify the richness of technological solutions and their status. The purpose is to help policy makers put these options in the context of the resilience challenges that they can help to address. These challenges are no longer problems for a futuristic renewables-dominated grid, they are becoming critical to ensuring resilience today, and are also becoming more acute with the lack of investment in grid modernisation over recent years. Technologies that are available today but not widely adopted – both digital and hardware – have the potential to reduce the costs of grid upgrades. Some of them, such as electricity storage and demand response technologies, can harness the incentives of end-users and power suppliers to innovate in ways that avoid some costs for TSOs and DSOs altogether. However, the near-term and long-term benefits of these technologies will only be realised if grid operators and regulators are encouraged to invest in them in accordance with their advantages compared to traditional solutions. This is of particular importance where the traditional technology – such as liquid-immersed transformers, overhead cables, lithium-ion battery storage, one-way communication or vacuum breakers – faces long construction delays or requires other grid upgrades in parallel to work effectively on today's changing grid.

The case for continued and strengthened innovation is evident in the suite of technologies that are becoming deployed today but were not readily available just one decade ago. This includes grid-forming inverters (see Chapter 5), dynamic line rating, high-temperature low-sag cables; VPPs and advanced high-fidelity models, including simulation tools like digital twins. Their availability is testament to innovation largely in the past two decades, mostly by researchers and companies in IEA Member countries that had the foresight to see upcoming challenges. However, it took time and publicly funded R&D for these technologies to move from the laboratory to commercial trials with companies, because of the lack of a clear near-term market. Today, there is a much clearer need for TSOs and DSOs to fit them into their investment cycles, for which further commercial refinements will be required.

Electricity grid terminology: a primer

Electricity grids are the world's largest co-ordinated machines, and this chapter uses terms that have precise technical meanings. The short definitions below are written for non-specialists and highlight why each concept matters for resilience and innovation.

- **Frequency**. The rate at which AC alternates, measured in cycles per second, Hz. It must remain very close to the system value (50 Hz in most of the world; 60 Hz in parts of the Americas and parts of Asia) across the whole interconnected area. Any mismatch between supply and demand causes frequency to deviate; operators use reserves and controls, and increasingly inverter functions, to correct frequency deviations second-by-second.

- **Synchronous operation and synchronous machines**. A term used when generators and equipment are locked to the same AC frequency as the grid. In a synchronous grid, thousands of rotating machines behave as one large machine, so any disturbance is felt system-wide in milliseconds.
- **Inertia**. The force that resists sudden frequency changes, giving time for controls and reserves to respond to a disturbance shortly afterwards. It is mostly provided by kinetic energy stored in rotating equipment (turbines, generators, synchronous compensators, and some industrial motors). Solar PV, wind turbines and batteries don't inherently provide inertia, but they can emulate it to a limited extent (so-called "synthetic inertia"). Synthetic inertia can be provided by kinetic energy stored in wind turbines, flywheels with power electronics, grid-forming inverters and E-STATCOMs.
- **Inverter**. A power-electronics device that converts DC to AC so resources like solar PV, batteries, and EVs can connect to the AC grid. Grid-following inverters need an existing voltage waveform (with a certain frequency) to latch on to. When coupled with battery storage, grid-forming inverters can set a stable voltage and frequency reference, helping keep the system stable at high renewable shares.
- **Transformer**. An electromagnetic device that steps voltage up or down, for instance up for efficient long-distance transmission to limit energy lost in transporting power; and down for safe distribution and use. Generally, it also provides electrical isolation and helps manage power flows.
- **Black-start**. The ability to restart part or all of the power system from a total shutdown, without relying on power from the main grid. It involves certain power plants, engines or batteries that can start on their own, energise key power lines and substations, and then help bring other power plants and loads back online in a controlled sequence. It can also be provided by neighbouring connected grids – France and Morocco supported the restart of the Iberian grids in 2025.

The technology landscape can be grouped according to four primary challenges that emerge from combinations of the different issues facing grid operators. The following section reviews the status, advantages and disadvantages of the different technologies that can address these challenges.

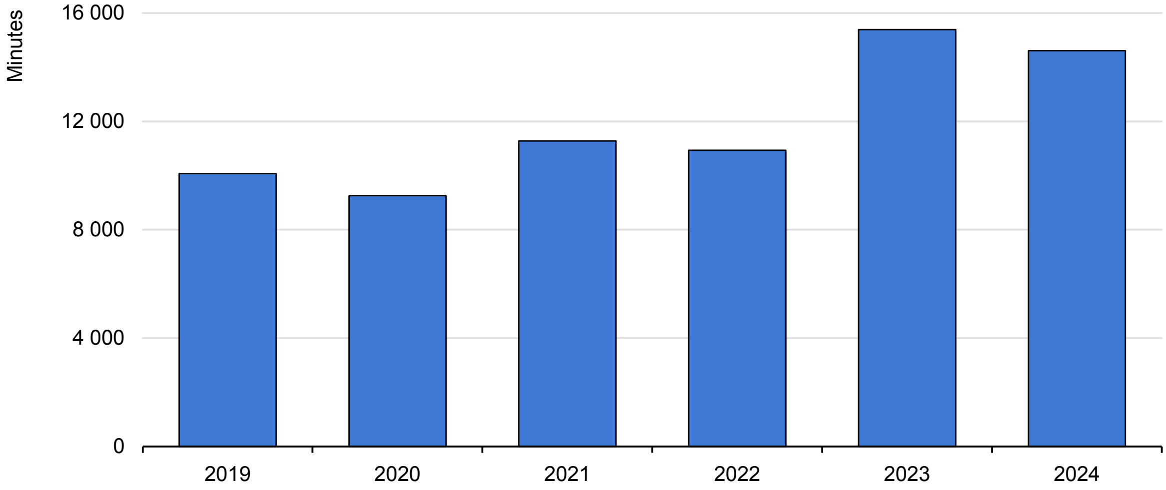
Four major technical challenges facing grid operators, and the contributing factors

Challenge	Issues contributing to the challenge	Sub-challenges
Ensuring real-time stability and power quality	• Rising variability of supply and demand • Changing geography of electricity supply and demand	• Maintaining voltage, frequency, grid strength and power flow stability • Protection and fault containment
Ensuring system adequacy and flexibility	• Rising demand • Changing geography of electricity supply and demand • Rising variability of supply and demand (and the accompanying rise of inverter-based generation) • Ageing infrastructure • Lagging progress towards full electricity access in emerging and developing economies	• Increasing grid capacity with minimal new infrastructure assets • Providing flexible capacity and flexible demand-side resources • Forecasting, planning and incentivising private investments in assets
Ensuring physical resilience	• Ageing infrastructure • Higher frequency and intensity of extreme weather • Threats of physical attacks on infrastructure	• Protection against physical threats • Hazard awareness and rapid restoration
Ensuring effective grid governance, interoperability and cybersecurity	• More cyber-attacks • Ageing infrastructure • Operational complexity of many more connected components and faster supply and demand changes	• Real-time monitoring and situational awareness • Advanced simulation • Cybersecurity for grid control systems

Technology landscape: ensuring real-time stability and power quality

Historically, maintaining real-time stability and power quality relied on large rotating components of power plants, like turbines, which spin at the system frequency (50 Hz of 60 Hz for most grids) and provide inertia to the system so that dips in frequency are quickly stabilised. In coming years, the shares of synchronous generators on many more grids are expected to contract as grids expand and inverter-based generators are more widely deployed. Frequency-related grid disruptions are on the rise. However, for some grids that are shifting toward high shares of non-synchronous generators, such as wind, solar photovoltaics (PV) and batteries, continuing to rely on synchronous generators for inertia is no longer the most cost-effective means of ensuring stability.

Total length of frequency deviations in the European Union, 2019-2024



Source: IEA analysis based on data from ENTSO-E (2024).

Grids must hold voltage locally and maintain grid strength (inertia) even while keeping frequency stable and power flows within limits. As synchronous plants retire, technologies that can do this without large rotating turbines are the real-time muscle of a modern system. TSOs and DSOs can site and operate them to strengthen weak nodes, absorb and supply power in milliseconds, set or support frequency, and re-route power around constraints. They can complement long-lead time transmission infrastructure by solving second-to-second stability and power-quality needs at substations, landing points for cables from offshore wind farms, data-centre clusters, vehicle charging hubs and congestions.

The technologies can be classified as follows:

- Maintaining grid stability and strength: voltage, frequency and a stable power flow
- Ensuring protection and fault containment.

Maintaining voltage, frequency and a stable power flow

The whole grid must operate within specific values to ensure real-time stability and power quality. "Grid strength" is a measure of whether grid voltages are resilient against uncontrolled, high fault currents. At a local level, connected assets, especially inverter-based resources, need a predictable grid and not a weak one prone to trips and oscillations. Technologies must address disturbances over timescales as short as a few hundred-milliseconds at individual grid nodes, such as substations or offshore hubs. These technologies are typically owned by or operated under contract to TSOs and DSOs, usually in front of the meter, which means that they are part of the grid and not located on a customer's premises.

Many of the relevant technologies for dynamic voltage control are already at TRL 9 and have demonstrated their effectiveness in advanced markets. However, their broader adoption is still hindered by regulatory challenges, lack of incentives, and business model barriers, preventing them from scaling up and reducing costs. Where responsibilities for voltage control are split between separate TSOs and DSOs, adoption of technologies at the distribution level that will benefit the whole system can be challenging. Interconnection with neighbouring grids can help, but where this isn't possible, local technical solutions are more important. In this section, some high-TRL technologies are summarised, followed by a box on three particularly promising earlier-stage technologies and then a table reviewing the full landscape in brief.

Some mature technology options are being deployed widely. **Synchronous condensers**, a long-standing technology first deployed in the 1930s, are back in fashion because they combine voltage support, fault current and inertia provision in one machine. ElectraNet, South Australia's transmission owner, installed multiple units to enable periods of 100% instantaneous renewables on the state grid. National Grid, Great Britain's electricity system operator, converted the retired Deeside gas site to run as a synchronous condenser. 50Hertz, the TSO for northeast Germany, is adding such machines to Baltic-coast landing points for offshore wind.

Very fast reactive-power devices, for example **static var compensators** and voltage-source **STATCOMs**, act like voltage "shock absorbers" at weak nodes. TSOs such as Energinet in Denmark and TenneT and 50Hertz in Germany deploy them at offshore hubs and interconnectors to smooth voltage during changes in wind energy output. On medium-voltage networks, technologies like automated shunt capacitor banks cut losses and lift voltages, as seen at Duke Energy in the United States and Enel in Europe and Latin America, while upgraded on-load tap changers keep PV-heavy feeders within limits, demonstrated by CenterPoint Energy in Houston and distribution network operator UK Power Networks in Great Britain.

A connected but separate challenge is ensuring stable system frequency and congestion management. These are not local issues but rather reflect behaviour of the entire system and typically occur over sub-second timescales to minutes. They are addressed via co-ordinated controls and market design. Technology responses control "active power" to maintain frequency after disturbances, reduce oscillations, and route power around bottlenecks. These technologies may be owned by TSOs, or by third parties remunerated through auctioned contracts for providing these services.

Among mature options, **automatic generation control** has been a mainstay of grid control since the 1960s. TSOs – including PJM and CAISO in the United States – are now pairing it with batteries so storage operations complement other generators. Indian TSOs POSOCO and Power Grid Corporation, as well as several European TSOs, are reworking **power system stabilisers** to calm disturbances before they spread. For power-flow control and to relieve bottlenecks without building new lines, technologies to make AC transmission systems more flexible are used:

- **Unified power-flow controllers** are used on key corridors by POSOCO, an Indian TSO.
- **Phase-shifting transformers** are used on cross-border ties such as Germany-Poland and Germany-Czechia.
- **Modular series devices** (such as advanced power flow controllers) are deployed to unlock headroom by Smart Wires, a services provider, and SP Energy Networks, a network operator, in the United Kingdom, and AusNet, a network operator in Australia.

High-potential emerging technologies for voltage regulation and fast frequency support

- **Grid-forming and meshed HVDC** (TRL 7). One-way HVDC point-to-point links are increasingly common for efficient long-distance transmission. The next technology horizon is multi-terminal systems, including offshore systems, and grid-forming voltage-sourced converters. Multi-terminal systems are demonstrated at a limited scale so far, usually only up to 3-4 terminals. However, they could enable "meshed" multi-terminal HVDC grids that share resources and bolster stability across interconnected regions via precise control of active and reactive power between asynchronous or weak AC areas. They would allow multiple high-capacity connections in remote locations, such as offshore or onshore wind, or ocean energy. One key component for such systems, fast DC circuit breakers, have been raised to TRL 8 in 2020 at the Zhangbei flexible DC grid in **China**, widely cited as the world's first four-terminal voltage-sourced converter-based DC grid. Operated by the TSO China State Grid, it integrates large volumes of wind, solar and storage. In **Europe**, a series of projects, of which the latest is INTEROPERA, are targeting multi-terminal HVDC systems with multi-vendor interoperability, especially for offshore use.
- **Grid-forming inverters** (TRL 8). Historically, the inverters that convert DC power from solar PV and batteries into AC were grid-following, which means that they could not influence frequency as they fed electricity into it. A technical upgrade allows them to establish voltage magnitude and frequency, provide virtual inertia and offer "black-start" capabilities if connected to an available power source, such as a battery (traditionally, a grid could only be restarted by synchronous generators after an outage). At least nine major grid-forming inverter projects, including the Hornsdale Power Reserve, are underway or in

operation in **Australia**, and others in **Europe** (such as the United Kingdom's Stability Pathfinder projects), **Asia** and **North America**. In Hawaii, an island grid with up to 90% renewable penetration at peak times survived the sudden loss of its largest generator because battery systems equipped with grid-forming inverters instantly responded to maintain frequency. However, standards and operational models are still under development: Australia and the United Kingdom are currently developing performance standards. More widespread use will require updating of grid regulations to include these devices, as well as further innovation in the areas of control software, interoperability and testing different mixes of grid-forming and grid-following inverters to guarantee stability (not all inverters will need to be grid-forming).

- **Solid-state transformers** (TRL 6). Unlike conventional transformers that use magnetic cores, solid-state transformers are built using semiconductor materials and power electronics, enabling compact, modular and highly controllable units. In addition to stepping voltage up or down, solid-state transformers can behave like STATCOMS or grid-forming inverters: they actively regulate voltage, ride through short faults, filter harmonics that disturb sensitive loads, and stream real-time condition data to operators. Because they natively handle both AC and DC and allow fully bidirectional power flow, solid-state transformers are especially well suited for connecting larger loads (or supplies, in the case of microgrids) like fast-charging hubs, electrolysers or some data centres. Solid-state transformers can isolate local faults in milliseconds, shield their users from the wider grid when it is stressed (so-called "islanding") and "heal" troublesome voltage pockets in dense urban areas or disaster-prone regions where space is tight and reliability is critical. Because they comprise modules of repeatable building blocks, their shorter manufacturing lead times may help alleviate transformer supply chain shortages. Modular architecture also reduces the cost of spare capacity, as entire spare transformers need not be maintained. Solid-state transformer modules may also extend the life of ageing traditional transformers by protecting them from further fault stress. Pilots are underway – such as in Singapore with Amperesand, a start-up, and the Port of **Singapore**. To become proven options for TSOs and DSOs, their cooling and protection systems must be shown to be robust, and a more diverse set of suppliers will be needed to help reduce costs, as seen previously for HVDC converters and inverters. To date, however, technical challenges such as part-load losses, high cooling demand, power-quality tuning and non-traditional fault behaviour have prevented solid state transformers from achieving cost and thermal performance targets, as well as ease of integration with legacy assets. Hybrid solutions that pair standard transformers with power electronics, such as that being tested in **Portugal** by IONATE, a **UK** start-up, and EDP, a grid operator, are having more success with addressing supply-chain and bankability risks.

Avenues of innovation for maintaining voltage, frequency and a stable power flow

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Automatic generation control (AGC)	Benefits: Mature since the 1980s. Keeps frequency on target by nudging multiple plants every few seconds. Reduces the need for manual adjustments. Limitations: Only effective if fast-reacting generators or storage are also available. Needs expert tuning to prevent oscillations that cause devices (like load-tap changers) to wear out.	9	Routinely used by **US** system operators such as PJM and CAISO to control battery fleets. In 2025, CAISO documented four-second AGC instructions and state-of-charge co-ordination for batteries. Decades of experience in Europe with the technology. In 2025, RTE, a **French TSO,** connected a type of AGC to the EU exchange of frequency restoration reserves.
HVDC link (incl. multi-terminal grid)	Benefits: Fast and efficient exchange of power between distant nodes increases stability. With voltage-sourced converters, provides black-start and inertia support. Limitations: Converter stations are expensive and complex. Multi-terminal HVDC grids need to prove control systems and need more investment in manufacturing of components like breakers.	9	In 2025, Hitachi Energy, a **Swiss** equipment supplier, announced it will supply a 675 km interregional HVDC link in the **United States** spanning three markets. In 2025, GE Vernova, a **US** supplier, proposed a Medium-Voltage DC onshore-to-offshore transmission system for up to 300 MW. In 2024, SSEN, a **UK** TSO, brought the first multi-terminal HVDC voltage-sourced converter interconnection in Europe into operation, using equipment from Hitachi Energy. In 2024, 50Hertz, a **German** TSO, awarded a contract for a 2 GW offshore voltage-sourced converter HVDC system to use equipment from Siemens Energy, a German supplier. In 2024, a **Dutch** TSO, awarded a contract to GE Vernova, a US supplier, for a 2 GW HVDC offshore system. In 2024, construction began at an USD 11 billion US HVDC link to use equipment from Hitachi Energy.
On-load tap changer	Benefits: Mature since the 1930s. Mechanical devices with high durability. Can maintain distribution-level voltage in areas with high PV penetration. Limitations: Poor co-ordination and tuning can cause devices to wear out. Use for local distribution is relatively new.	9	In 2025, UK Power Networks, a **UK** DSO, announced a digital tap-changer control roll-out. In 2024, Maschinenfabrik Reinhausen, a **German** equipment supplier, reported cumulative sales of 15 000. Recent advances focus on voltage optimisation and Con-Edison, a **US** distribution utility, reported 2% energy savings from a large-scale programme of smart control of on-load tap changers.

Shunt capacitor, including mechanically switched damped capacitor networks	Benefits: Mature since the 1930s. Low-cost means of supporting steady state voltage control at feeders and substations. Limitations: Relatively slow response. Less effective for deep voltage dips. Needs good co-ordination to avoid causing unnecessary power surges.	9	Maturity and standardisation is evidenced by design guidance from EPRI, an alliance of **US** utilities, and from Duke Energy, a US utility; case studies from Schneider Electric, a French equipment supplier, are available. In 2024, EVN, a **Vietnamese** TSO, completed shunt capacitor installations at eight 220-kV substations to boost voltage support ahead of summer demand.
STATCOM / Static Var Compensation (SVC)	Benefits: Technologically mature since the 1970s (SVC) and 1991 (STATCOM). Maintain voltage during deviations by injecting or absorbing reactive power. Limitations: Do not provide inertia. Power electronics need filters, cooling and can be large. Currently relatively costly.	9	In 2024, ESB Networks, an **Irish** DSO, 50Hertz, a **German** TSO and Transpower, a **New Zealand** TSO, commissioned new STATCOMs to bolster voltage support and hosting capacity. Ørsted, a **Danish** developer, commissioned the first STATCOM for offshore wind in the **United Kingdom**, using equipment from Hitachi Energy.
Synchronous condenser (also called synchronous compensators)	Benefits: The fundamental technology is around 100 years old. A large rotating machine powered by electricity to provide spinning inertia, and absorb or inject reactive power for voltage support and fault current protection. Can be converted old power plants. Limitations: Response times are too slow for converter-rich networks. Large. Relatively expensive. Losses of 1-3%. Need mechanical upkeep.	9	In January 2026, Hanwha Energy, a **Korean** developer, commissioned a 4 GW-second synchronous condenser in **Ireland** using technology from Siemens Energy, a **German** supplier. In January 2025, NESO, a **UK** TSO, commissioned a new synchronous condenser with equipment from Siemens Energy. In 2024, EirGrid, an **Irish** TSO, awarded contracts for new synchronous condensers In 2024, LCRA, a **US** TSO, announced synchronous condenser purchases.
Other FACTS (flexible AC transmission systems) technologies	Benefits: Thyristor-controlled series capacitors, unified power flow controllers and synchronous series compensators (SSSC) steer flows and stabilise voltages on congested corridors. Can unlock capacity without new cables. Limitations: High cost and complexity.	8	In 2025, ISA Energia Brasil, a **Brazilian** TSO, began installing modular static synchronous series compensator (SSSC) devices at a substation. The first of its kind in Brazil. In 2025, ELES, a **Slovenian** TSO, deployed 24 SSSC modules on an interconnector, with **EU** funding support.
E-STATCOM	Benefits: In addition to traditional STATCOM benefits, super-capacitors give short bursts of active power within milliseconds, creating synthetic inertia.	7	In 2025, Siemens Energy, a **German** equipment supplier, commissioned the first E-STATCOM pilot with TenneT, a German TSO, alongside a German wind farm.

	Limitations: While R&D began in 2012, experience is limited to a small number of pilots.		In 2025, Hitachi Energy, a **Swiss** equipment supplier, advanced the construction of its first two E-STATCOM pilots in Germany with TransnetBW, a German TSO.
Grid-forming inverter	Benefits: Provide inertial response when paired with an energy source. Allow invert-based resources to set the voltage magnitude and frequency on the grids to which they connect. Support black-start. Small and modular units. Limitations: Standards, models and protection practices are still maturing. Do not yet protect against fault currents.	7	In 2025, NESO, a **UK** TSO, connected the first grid-forming battery to its transmission system. In 2025 Schoenergie, a **German** developer, commissioned Germany's first utility-scale grid-forming inverter battery as part of a government-funded research project. In 2024, Plus Power, a **US** developer, began operating a battery plant with grid-forming services for Hawaiian Electric, a US TSO.
Solid-State Transformer	Benefits: Fast, programmable voltage control and power-quality conditioning. Enables bi-directional controllable flow on medium voltage grid. Transformer: Not yet manufactured or tested at scale on grids. Thermal control and interoperability need further development. Costs remain high.	6	In 2024, the **US** government funded a demonstration by GE Vernova at a public-utility substation and financed a laboratory testing project by Resilient Power Systems, a US start-up. In 2025, a 1-year trial of Amperesand's technology for EV charging, spun out from a **Singaporean** public university, began. In 2023, IONATE, a **UK** start-up, and EDP, a **Portuguese** TSO, piloted hybrid transformer designs on residential grids in Portugal and **Spain**.

Protection and fault containment

When something goes wrong, a branch hits a line or equipment fails, the grid has milliseconds to detect, isolate and recover before a small problem becomes a large outage. New protective relays and high-speed communications clear faults and restore power supply faster and more precisely.

Among proven and deployed technologies, **Autoreclosers** restore power automatically after brief faults and, combined with automated switching, they reduce the area affected by an outage. TSOs such as EPB Chattanooga and SDG&E in the United States, and Enedis in France, already use such fault location, isolation and service restoration (FLISR) systems. To protect against fires, US utilities such as PG&E and SCE have employed fast-trip settings, cutting power almost instantly to prevent ignitions. Recent innovation relates to advanced autoreclosing at the distribution system level.

Beyond improving individual devices, combining them and integrating them into grids is an ongoing technology innovation challenge. Examples include combining grid-forming inverters and synchronous condensers for inertia support, coordinating HVDC and FACTS devices for oscillation damping, maintaining system integrity under severe disturbances, and using AI to tune the control of thousands of connected grid devices. Some 39% of grid-related AI patents target forecasting and decision-making for grid stability, and the underlying algorithms can be continuously improved.

High-potential emerging technology: fault current limiters

- **Superconducting fault current limiters** (TRL 7). As grids grow more interconnected and generators connected directly to distributed grids rises, the potential for high short-circuit currents during faults grows. Fault current limiters use advanced materials such as superconductors or power electronics to instantly suppress surges in current during a fault, thereby "softening" short circuits and protecting equipment including transformers and breakers. In this way, service can be restored more quickly. It is expected that by deploying them at strategic points, DSOs will avoid costly network reconfiguration or over-sizing of equipment for rare events. Field trials are ongoing on dense city networks in **Korea** and the **European Union**. Costs still need to be reduced and reliability improved through innovation before they become standard options in grid design.

Avenues of innovation for grid protection and fault containment

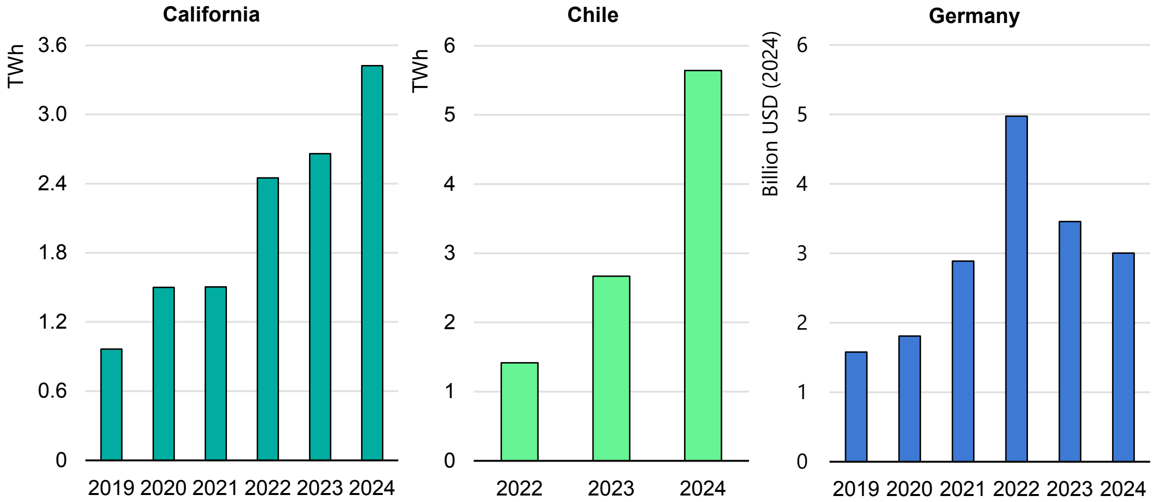
Technology	Potential benefits and limitations	TRL	Examples of recent advances
Autoreclosers	Benefits: Core technology is standard for TSOs since the 1970s. Quickly restores power after momentary faults. Limitations: Without expert tuning, faults can recur. May need to be disabled in wildfire seasons. Needs further refinement for DSOs.	9	In 2024, SA Power Networks, an **Australian** DSO, installed a 33 kV recloser and updated protection settings as part of a non-network reliability project. In 2025, G&W Electric, a **US**-based equipment supplier, unveiled a next-generation Viper-ST recloser with higher ratings and automation-ready controls.
Fast-trip settings	Benefits: Instantly disconnects power in abnormal conditions, e.g. to prevent igniting wildfires. Limitations: Can increase risks of outages from faults that would otherwise clear. Needs accurate data inputs to avoid over-tripping.	9	In 2025, PG&E, a **US** utility, reported Enhanced Powerline Safety Settings (EPSS) that contributed to a 65% reduction in reportable ignitions vs. 2018–2020 average. In 2025, Southern California Edison, a **US** utility, documented fast-trip operations during elevated fire risk, aligned with state Protective Equipment and Device Settings policy.

Protective relaying systems	Benefits: Digital relays have been deployed since the 1990s. Can detect and clear faults in milliseconds to prevent cascades. Can co-ordinate over wide areas. Limitations: Periodic testing, telecom availability and model accuracy are essential to avoid malfunction.	9	In 2025, RTE, a **French** TSO, deployed LF Energy SEAPATH for virtualised protection and automation, with the first substation online in 2023 and a plan to reach 100 such substations. In 2024, IGNIS, a **Spanish** developer, completed Spain's first IEC 61850 process-bus digital substation.
Distribution automation and fault location, isolation, and service restoration (FLISR)	Benefits: Mature since the 2010s. Automatically isolates faults and reroutes power so fewer customers lose supply. Limitations: Dependent on telecommunications systems.	9	In 2024, Duke Energy Florida, a **US** utility, reported deployments saved 300+ million outage-minutes during Hurricanes Helene and Milton. In 2024, Enel Distribución, a **Chilean** electricity distribution company, reported deployment of 2,800+ telecontrol devices, enabling rapid fault isolation and restoration in Santiago's network.
Fault current limiters (FCLs)	Benefits: Instantly caps fault current to protect equipment and maintain voltages in dense networks. Limitations: Superconducting versions (TRL 8) have higher costs for cooling and maintenance. Power-electronic fault current limiters add losses and complexity.	9	Mechanical FCLs have been on the market for many years and are widely used; first super-conducting FCL available since 2009. In 2024, Nexans, a **French** equipment supplier, and SNCF Réseau, a **French** rail infrastructure manager, announced deployment of a superconducting fault current limiter for rail electrification, scheduled to enter service in 2025. In 2025, SuperGrid Institute, a **French** research institute, demonstrated first 50 kV DC breaking by combining a superconducting FCL with a DC circuit breaker.

Technology landscape: ensuring system adequacy and flexibility

Ensuring system adequacy means having sufficient resources to meet electricity demand at all times, including during peaks and emergencies. Doing so with high resilience means that there must be sufficient capacity and redundancy to withstand and recover from shocks, such as extreme weather or major equipment failures. It also reduces the costs incurred by too much congestion on the network. A range of technologies can be applied at different points on the distribution or transmission grid, including “behind the meter” at a customer's premises, to avoid needless overcapacity, diversify power supplies, and allow modular systems to reconfigured in emergencies. For grid operators, ensuring sufficient capacity can also be achieved by refurbishing infrastructure so it can carry more power and with new digital tools that optimise the utilisation of existing grid capacity. In addition, accurately forecasting the availability of distributed resources is becoming a more important element of adequacy. This can reduce curtailment (wastage) of power that is generated but not used.

Trends in renewable electricity curtailments in California and Chile, and grid congestion costs in Germany, 2019-2024



Sources: IEA analysis based on CAISO (2024), Coordinador Eléctrico Nacional (2024), Bundesnetzagentur (2024).

Flexible capacity and demand-side resources

Technologies in this category cover challenges over hours to days, making sure there is always enough capacity and flexibility to meet demand, even during extreme weather or renewable energy scarcity. The relevant technologies are mature and generally well-understood by grid operators, though they are new enough for many DSOs and TSOs to be hesitant about relying on them for urgent capacity needs.

Grid management technologies, such as **advanced distribution management systems (ADMS)** and **advanced energy management systems (AEMS)** are typically owned by DSOs and TSOs to help them schedule grid-wide resources more quickly to avoid congestion in response to changes in supply and demand. These types of management systems can avoid the need for investment in infrastructure redundancy for peak periods.

Flexible demand and supply capacity technologies are more likely to be owned by third parties, such as independent power producers, electricity retailers or aggregators. These firms are financially incentivised to flex the assets that they control in response to signals from the grid or the grid operator, in order to match real-time supply and demand at lower cost than adding new power generation capacity. The remuneration is typically contracted via auctions for capacity availability. Demand response technologies enable customers to be compensated for trimming or shifting usage at crunch times. While curtailment of a few large industrial consumers has long been possible, such approaches have become much more sophisticated with recent improvements in digital technologies and cost reductions for sensors. **Distributed energy resource management systems (DERMS)** are digital protocols and processes that allow very large numbers of assets – heaters, appliances, batteries, vehicles, industrial processes and small generators – to be remotely and automatically co-ordinated to provide large amounts of demand response to the grid. When DERMS are connected to many units they can be mobilised with the reliability and scale of a major power plant. Aggregation in this way is known as a **virtual power plant (VPP)**. The deployment and optimisation of VPPs is highly dependent on market rules that reward more flexible demand, for example via payments for ancillary services or by enabling time-of-use tariffs.

Flexible capacity and demand-side resources

Technology	Potential benefits and limitations	TRL	Examples of recent advances
ADMS and AEMS	Benefits: Mainstream since the late 1990s. Allows live view of local grids, smart switching and voltage control. Faster restoration. Lower losses. Limitations: Complex IT integration. Needs lots of connected devices in the field.	9	In 2024, state-owned **Dubai** utility DEWA launched its Distribution Network Smart Centre, automating responses using daily data from the distribution grid.
VPP and DERMS	Benefits: Creates additional flexible capacity without requiring major infrastructure. Allows owners of batteries and EV chargers to monetise their full value. Limitations: Grid operators are often cautious about accepting VPPs as firm capacity. Requires inter-operability and cybersecurity standards for third party assets. Hard to create sufficient economic incentives for end-users to participate.	9	Kraken, an energy technology platform owned by **UK** energy supplier Octopus Energy, now orchestrates over 2 GW of power across 500 000 devices. In **France**, Voltalis, a start-up, accumulates just below 1 GW of demand response capacity and announced closing finance on 1.4 GW of new DR capacity. In 2024, Schneider Electric, a French equipment supplier, announced advanced DERMS deployment with Elektrilevi, an **Estonian** DSO. In 2024 in **Singapore**, SP Group piloted a DERMS to manage solar, storage and EVs on its distribution network.
Grid-scale lithium-ion battery	Benefits: Deployed for grid-scale applications since 2012. Can balance grids fast. Is now well understood and economical. Can provide other support services to address multiple grid challenges, including black-start and system restoration, synthetic inertia and supporting frequency. Limitations: Typically only stores power economically for 1-4 hours.	9	Global installations have now reached around 500 GWh, with investment of around USD 30 billion in 2025. In 2024, Terra-Gen, a **US** developer, commissioned 3 287 MWh, the largest in the country at a single site. In 2025, Zenobē, a **UK** developer, deployed a 400 MWh (minimum 2-hour discharge time) battery, the first grid forming battery on the **UK** transmission grid. In 2025, Edify Energy, a developer, reached commercial operations of a 370 MWh (minimum 2-hour discharge

	time) BESS with grid-forming inverters in **Australia**. In 2025, China Huadian, a **Chinese** generator, commissioned 2 000 MWh (minimum 4-hour discharge time). In 2025, **Saudi** Electricity Company, a utility, connected three transmission-level assets of 2 600 MWh each.

Long-duration and seasonal energy storage

Week-long heatwaves or prolonged calm winds pose a new adequacy challenge – they can create multi-day supply-demand imbalances that conventional 4-hour lithium-ion batteries cannot resolve economically. Long-duration energy storage (LDES) technologies are capable of discharging economically after more than 4 hours of storage, and sometimes after several days, depending on the types. Before the 2010s, practically all storage capacity was pumped hydro, which can hold water for long periods before generating electricity, but it is regionally constrained and needs disruptive, large civil engineering works.

Multiple less-mature technologies are in the later stages of development, including **compressed air**, **liquid-air**, **flow batteries** and **iron-air batteries**. While some may be bought by TSOs and DSOs, many will be owned and operated by third parties. Leading examples include an iron-air battery being piloted at 1.5 MW scale (minimum 100-hour discharge time) in the United States by Form Energy, a start-up, and a CO_2 liquefaction cycle that is operated at a 20 MW scale (minimum 10-hour discharge time) in Italy by Energy Dome, a start-up. Flow batteries, including vanadium redox flow, have shown promise in 8-12 hour applications, but further innovation is required to improve their cost and energy density before large-scale projects start.

Achieving the cost reductions that can expand the market for LDES will likely require breakthroughs in chemistry and scale. Finding ways to rely mostly on abundant materials (iron, sodium, zinc) instead of scarce metals, and mass-manufacturing new battery systems will be important. However, they will not progress without parallel work on supportive market design so that the value of resiliency (e.g. supplying the grid during a 3-day outage) can be monetised to justify investments. Some regions are introducing capacity credits or contracts for long-duration storage, learning from experiences in places like California in the United States, which has begun procuring storage of 8 hours or more for reliability needs.

Avenues of innovation for long-duration energy storage (for electricity-to-electricity round trips)

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Mechanical (gravity e.g. pumped hydro, compressed or liquified air)	Benefits: Pumped hydro and compressed air are fully mature with long lifetimes. Usually linked to turbines so can provide inertia, fault current and voltage support. Limitations: Large pumped hydro and compressed air are highly site-dependent. Long development times. High individual project costs. Compressed air may need an external heat source.	9	In 2025, a 4 200 MWh (minimum 6-hour discharge time) compressed air project by **Chinese** developer ZCGN, was cleared for construction in China. In 2025, a 2 000 MWh (minimum 8-hour discharge time) in Kidston, **Australia** pumped hydro hit key installation milestones, tracking toward completion in early 2026. In 2025, Highview Power, a **UK** developer, advanced **UK** LDES projects under the government's cap-and-floor scheme (multi-GWh pipeline). In 2025, Energy Dome, an **Italian** start-up, started operation of its 200 MWh (minimum 10-hour discharge time) demo plant in Italy**,** for which it has signed an offtake deal with Engie, a French network operator.
Flow batteries (vanadium / iron flow)	Benefits: Low degradation at deep discharge makes it well-suited to more than 6-hour storage. Power and energy capacity can be sized independently. Limitations: Lower round-trip efficiency and lower energy density than Li-ion means more space required. High balance-of-plant cost. Small existing manufacturing base. Vanadium batteries are dependent on vanadium prices.	8	In December 2025, Rongke Power, a Chinese vanadium flow battery developer, commissioned a 1 GWh (5-hour minimum discharge time) in **China**. In 2025, SRP, a **US** utility, selected ESS Inc's 50 MWh (10-hour minimum discharge time) iron-flow battery for an LDES pilot in the **United States**. In 2024, Sumitomo Electric, a **Japanese** equipment supplier, commissioned a 8 MWh (8-hour minimum discharge time) vanadium redox flow battery alongside municipal renewables deployment.
Thermal (water, molten salts, solid media)	Benefits: Uses cheap, widely available materials (water, salts, concrete, rocks, sand). Can retain heat for long periods. Usually linked to turbines so can provide inertia, fault current and voltage support. Limitations: Large tanks or pits require space. Newer concepts are at pilot or first-of-a-kind scale. Turbines required to convert heat to electricity, lowering efficiency.	8	In 2025, RAYGEN, an **Australian** start-up, raised USD 80 million in equity to help develop its water-based storage technology at a scale of 720 MWh (minimum 8-hour discharge time). In 2024, Malta Inc., a **US** start-up, broke ground on full-scale heat-exchanger qualifications under Store2REPower, enabling its pumped-heat storage. In 2025, Malta Inc. signed to develop a 14 MWh demonstration plant in **Spain**.

			In 2022, Høje Taastrup and VEKS, two **Danish** district heat suppliers, deployed a 70 000 m³ water-storage pit.
Multi-day electro-chemical (iron-air)	Benefits: Abundant, low-cost materials (iron, water, air) keep costs low and avoids critical minerals. Very safe. Good for providing energy capacity when needed. Limitations: Lower round-trip efficiency and slower response than Li-ion means that it cannot provide frequency and voltage support. Much larger physical footprint than Li-ion. Lacks proven real-world experience.	6	In 2024, Great River Energy, a **US** utility, and Form Energy, a US start-up, broke ground on a 1.5 GWh (100-hour minimum discharge time) plant in the United States.

Seasonal storage is a separate category of even longer duration storage. It is expected to need very large scales and very low capital costs to be economic over months of storage without depletion. Making **hydrogen** and storing it in underground caverns is one option, and another is to heat up **thermal pits** that maintain high temperatures into winter. However, round-trip efficiency can be low and additional infrastructure – electrolysers, caverns, turbines – are required. Some projects for hydrogen storage in the United States and Europe are underway but viable market conditions for investment are not yet developed. For thermal storage, the economics of converting the heat back to electricity are often poor due to the low temperatures involved, especially for water-based storage. Without producing electricity, these technologies are unsuitable for supporting grids with dispatchable capacity or inertia. They may nevertheless have value if they can discharge heat and thereby reduce demand for electricity for heating or cooling at peak times.

Avenues of innovation for seasonal energy storage (for electricity-to-electricity round trips)

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Thermal (water, molten salts, solid media)	Benefits: Uses cheap, widely available materials (water, salts, concrete, rocks, sand). Can retain heat for long periods. Usually linked to turbines so can provide inertia, fault current and voltage support. Limitations: Not yet developed for regenerating electricity, limiting its use for grid resilience. Turbines required to convert heat to electricity, lowering efficiency.	8	In 2025, Polar Night Energy, a Finnish start-up, commissioned a 100 MWh sand battery' delivering 1 MW thermal to a district heat network in **Finland**, not for the power grid. In 2024, Semco Maritime, a **Danish** engineering company, inaugurated a molten-salt demonstrator in Esbjerg to store renewable electricity as heat for district heating, not for the power grid.

Hydrogen in salt or rock caverns	Benefits: Very large scale. Can absorb electricity and regenerate power with turbines (which can provide inertia, fault current and voltage support) or fuel cells. Builds on knowledge and infrastructure for natural gas storage. Limitations: Low efficiency. Very high upfront cost and long lead times. Geographically constrained. Regulatory frameworks, market design and business models are still emerging.	6	In 2025, ACES Delta, a **US** developer, began injecting hydrogen to prepare to supply a hydrogen-capable power plant in coming years from two caverns sized for around 300 GWh. In 2025, a consortium of **Swedish** energy, mining and steel companies demonstrated hydrogen storage in a lined hard rock cavern (at roughly one-thousandth commercial scale). In 2025, a consortium of **Japanese** equipment suppliers demonstrated land-based use of marine hydrogen engines that could be used with stored hydrogen at distributed sites.
Ammonia and other hydrogen-based synthetic fuels	Benefits: Easy to store in tanks. Extensive existing trading infrastructure and can be used in existing power plants. Usually linked to turbines so can provide inertia, fault current and voltage support. Limitations: Low efficiency, which significantly raises total costs of delivered electricity. 100% ammonia generators still under development.	5	In 2024, JERA, a **Japanese** power generation utility and IHI, a Japanese equipment supplier, achieved 20% ammonia co-firing at a 1 GW unit with stable emissions performance. In 2025, Baker Hughes, a global equipment supplier, and Hanwha, a **Korean** equipment supplier, announced a partnership to develop small ammonia turbines.

Increasing grid capacity with minimal new infrastructure

A range of technologies are available to enable existing cable capacity to carry more power. Among mature technologies, **advanced conductors** on existing routes have been shown to almost double their capacity in the United States and Spain. **Power-flow controls** reroute electricity away from congested lines to avoid the need to increase their capacity, as seen in the United Kingdom or in Australia. **Advanced distribution management systems** and **advanced Energy aanagement systems** – also used to manage flexibility (see above) – let operators tweak voltages and reconfigure networks automatically. In addition, advanced power control technologies, such as STATCOMS and smart transformers (above), can boost grid carrying capacity.

High-potential technology awaiting wider adoption: dynamic line rating

- **Dynamic line rating (DLR)** (TRL 9). Instead of always using the same fixed limit, grid operators can adjust and safely expand the limit when weather conditions are conducive. For example, when it is cold or windy, the lines become physically cooler, allowing them to carry more electricity. Global experience shows that typically, transmission lines can safely carry 20-30% additional capacity above their maximum rating for around 90% of the time in any given year. This is important because equipment connected to the edges of the distribution grid is limited to these maximum ratings, which can be restrictive. DLR, especially when coupled with AI, helps evaluate when to use this capacity instead of other options, such as curtailing renewables because of a lack of grid transfer capacity, or building a whole new line to accommodate new peak flows. It is estimated that DLR systems could activate 115-175 GW of additional global transmission capacity at a fraction of the USD 35-52 billion cost of equivalent new power lines. in the United States, on implementing DLR, PPL Electric Utilities saved USD 64 million in 1 year by avoiding congestion costs on a single line. While some TSOs have embraced DLR, the majority of grid operators lag behind, mainly for regulatory and budget, rather than technical, reasons.

Avenues of innovation to use existing network capacity to carry more power

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Advanced conductors: high-temperature low-sag, aluminium conductor composite core, and carbon-core high-temperature	Benefits: Allows upgrading of existing lines to carry more power instead of new lines. Limitations: Some existing infrastructure may not be suitable for upgrade. Substation and protection settings may not be compatible. Lines are unavailable during upgrade.	9	In 2025, the Board of CAISO, a **US** system operator, approved transmission projects including reconductoring with advanced conductors to boost capacity without new corridors. In 2025, Google, a **US** ICT technology provider, and CTC Global, a **US** equipment supplier, announced an initiative to expand **US** transmission capacity and supply chain for advanced conductors. In 2025, the **US** government guaranteed a USD 1.6 billion loan to AEP to rebuild and reconduct around 5 000 miles across five states.
Dynamic line rating, line and corridor monitoring	Benefits: Real-time data allow 10-30% more power to be carried on existing capacity, avoiding new infrastructure.	9	In 2025, National Grid, a **UK** TSO, installed dynamic line-rating sensors across around 275 km of circuits to

	Allows damage to be spotted quickly after disruptions. Limitations: Requires sophisticated communications, data and image processing. Benefits are lower where weather is less variable.		unlock capacity and cut constraints. In 2024, Great River Energy, a US utility, and Heimdall Power, a Norwegian equipment supplier, launched the largest US DLR deployment to date with 52 sensors. In 2023, Energinet, the **Danish** TSO, reported 30% more transmission capacity for 90% of the time on around 20 lines.
High temperature super-conductors, cables and fault current limiters	Benefits: Very low losses allow much higher capacity on existing power lines. especially in dense urban areas. Limitations: Need for cryogenic cooling as low as -196°C adds complexity, cost and auxiliary energy use. Limited field experience outside pilots and short connections.	8	In 2024, SWM Munich, a **German** DSO, commissioned the world's first 110 kV high temperature superconducting cable at a substation, with equipment from THEVA, a German supplier. In 2025, KEPCO, A **Korean** DSO and TSO, announced a superconducting power grid for a large data centre, with equipment from LS, a Korean supplier. In 2025, SuperGrid Institute, a **French** firm, demonstrated a first 50 kV DC circuit breaker and fault current limiter combination.
Topology optimisation and power flow control	Benefits: Routes electricity via less congested power lines, freeing up capacity and reducing curtailment. Limitations: Requires sophisticated communication and control systems. Has not yet gained operators' full trust for automated use.	8	In 2024, National Grid, a **UK** TSO, launched a project with Smart Wires to reduce bottlenecks using topology optimisation and Advanced Power Flow Control (APFC). In 2025, PG&E, a **US** utility, and Smart Wires, announced APFC deployment to unlock over 100 MW at a **US** substation for new loads.

Forecasting and short-term planning

To ensure system adequacy and flexibility, grid operators increasingly depend on advanced forecasting and planning tools. Retaining versatility towards different views of future demand, renewable output and network scenarios, across different timescales, are essential to using existing assets more efficiently, deferring new investment where possible and spotting adequacy gaps early.

AI and probabilistic methods are now available to help grid operators anticipate swings in electricity generation and spikes in demand. These technologies are critical for analysing the wealth of data that is necessary for accurate forecasting and precise real-time adjustments. While they have mostly been proven in real-world tests, many grid operators are only beginning to explore their potential.

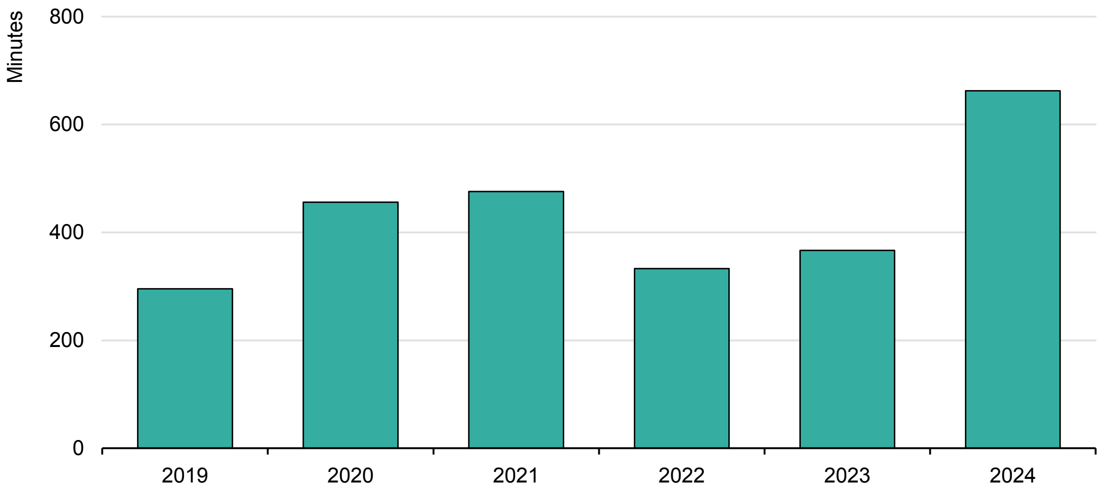
Avenues of innovation for improved forecasting and planning

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Contingency analysis tools	Benefits: Regular running of possible scenarios helps warn of upcoming issues and prevents cascading faults. Limitations: Highly dependent on model accuracy and high computing power.	9	In 2024, CAISO, a **US** system operator, adjusted Real-Time Contingency Analysis and dynamics monitoring parameters to improve stability and accuracy in operations. In 2025, 50Hertz, a **German** TSO launched a market-sounding to introduce Dynamic Security Assessment software for real-time stability analysis.
Renewable generation forecasting	Benefits: Improving forecast accuracy helps grid operators to maximise use of available supply resources. Limitations: Further development needed to account for terrain and fast-moving weather patterns.	9	In 2025, NESO, a **UK** TSO, reported its Solar NowCasting project improved PV forecasts using deep learning and open data tools. In 2025, AEMO, an **Australian** system operator updated its forecasting methodology to better capture consumer energy resources including renewables. In 2025, Energinet, the **Danish** TSO, and DMI, the Danish Meteorological Institute, began working to update weather forecasts every 10 minutes instead of 3 hours. In 2025, IESO, a **Canadian** system operator, revised guidance for variable generators to submit their own forecast in day-ahead markets.
Load forecasting systems	Benefits: Using AI to improve forecast accuracy for demand helps grid operators to reduce the number and impact of unanticipated events. Limitations: Models need regular retraining. Errors related to user behaviour are common.	9	In 2025, NYISO, a **US** system operator, highlighted rising large-load interconnection requests (data centres, chips) reshaping demand forecasts. In 2024, IESO, a **Canadian** system operator, revised demand forecasting methods in its Annual Planning Outlook.
AI-powered analytic platforms	Benefits: Improved prediction of grid inertia, strength and fault levels, for visibility of potential outages and scheduling of maintenance. Limitations: AI must be trusted without knowledge of its processing or visibility of data inputs. Can be a major culture change for grid operators.	7	In 2024, Hitachi Energy, a **Swiss** equipment supplier, launched an AI-powered energy forecasting solution to improve utility and market participant decision-making. In 2025, Amperon, a **US** start-up, expanded to AI-powered price and mid-term load forecasts to support trading and battery dispatch strategies. In 2025, Sentient Energy, a **US** equipment supplier, launched an AI platform that uses line-sensor data to predict impending outages for targeted maintenance.

Technology landscape: ensuring physical resilience

Grid-hardening technologies are those that help physical grid infrastructure to better survive hazards. Examples include insulated or covered conductors and fire-resistant poles in wildfire zones, spark prevention units, submersible switchgear in flood-prone areas, pole reinforcement in earthquake-prone regions or burying of cables in hurricane corridors. Many utilities are deploying such measures. In the United States, Californian utilities have covered hundreds of miles of bare line and added fast-acting remote switches to mitigate wildfire ignitions. Similarly, mobile substations and generators are being procured as contingency assets to restore power quickly if a substation is knocked out (a type of "first-aid kit" for the grid).

Average duration of grid interruptions in the United States, 2019-2024



Source: IEA analysis based on data from US Energy Information Administration (2025).

While the hardware solutions in these cases are mostly commercially available, with many at TRL 9, there is considerable ongoing technological innovation in digital technologies to prioritise and optimise their use, reducing costs and increasing effectiveness. Data-driven risk modelling – including using AI to analyse asset condition and weather patterns – can pinpoint which circuits to harden first for maximum resilience gain. Moreover, networks of new sensors – wildfire detection cameras and satellite thermal imaging – feed into these tools to give early warning to grid operators. A more resilient grid will come from better planning informed by better data, and targeted deployment of both high-tech solutions (like automated reclosers with adaptive settings) and low-tech upgrades (like elevating substations or planting windbreaks around lines). Changes to regulatory frameworks can help encourage their use, with some regions now allowing "performance-based" incentives for resilience improvements, thereby rewarding utilities for innovative reliability measures that prevent outages during disasters.

Avenues of innovation for grid-hardening, hazard awareness and rapid restoration

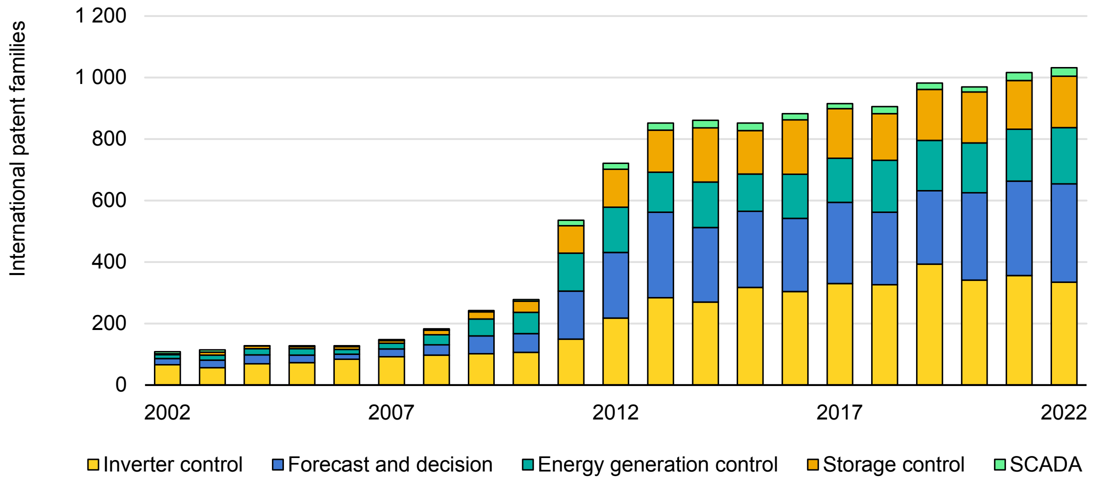
Technology	Potential benefits and limitations	TRL	Examples of recent advances
Asset health monitoring (transformers, circuit breakers, corrosion, structures)	Benefits: Detects overheating, rust, leaning pylons or poles etc. early, avoiding outages and extending lifetimes. Limitations: Data needs expert interpretation. Costs need to be reduced through scaling.	9	In 2024, GE Vernova, a **US** equipment supplier, and Systems With Intelligence, agreed to integrate infrared thermography, with first product availability in early 2025. In 2025, Vaisala, a **Finnish** supplier, introduced enhanced transformer monitors for automated condition assessment.
Covered conductors	Benefits: Reduce sparks to lower wildfire risks. Limitations: Heavier and costlier than standard cables. Needs more periodic inspections.	9	In 2025, Southern California Edison, a **US** utility, outlined installing up to 1 200 circuit-miles of covered conductor in high fire-risk areas. In 2025, the CPUC, a **US** regulator in California, ratified Energy Safety approval of the 2025 Wildfire Mitigation Plan update from PG&E, a **US** utility, which includes covered conductor deployments.
Grid-hardening insulation and fire-resistant equipment	Benefits: Tougher poles, insulators and transformers survive fire and harsh conditions. Limitations: Requires extensive retrofits for benefits that are more marginal than more innovative solutions.	9	In 2024, Bonneville Power Administration, a **US** system operator, reported fire-resistant wrap protecting transmission wood poles during a recent wildland fire. In 2025, the wildfire plan from PacifiCorp, a **US** grid operator, documented ongoing replacement of wood poles with composite or steel poles in high-risk areas..
Self-healing networks	Benefits: With pervasive sensors and controls, grids can have the capacity to automatically reconfigure themselves or isolate microgrids to stop outages spreading. Limitations: Requires a very high level of digitalisation and telecommunications that most grids do not yet have. So far limited to small areas.	9	In 2024, Duke Energy Florida, a **US** utility, reported self-healing tech isolating faults and restoring customers rapidly during back-to-back hurricanes. In 2025, CenterPoint Energy, a **US** utility, surpassed the mid-point of its Greater Houston Resiliency Initiative, deploying automation for a self-healing grid. In 2025, Florida Power & Light, a **US** utility, highlighted ongoing installation of self-healing smart-grid devices as part of storm hardening.

Underground power lines	Benefits: Buried lines are less affected by weather and fires. Limitations: Costs are 5-10 times higher than overhead lines. Repairs are slower and more expensive.	9	In 2025, PG&E, a **US** utility, announced it has constructed and energised 1,000 miles of underground powerlines in high fire-risk areas. In 2025, Florida Power & Light reported 3 000 Storm Secure Underground Program projects since 2019; performance 5-14 times better during the 2024 hurricane season.
Environmental and hazard monitoring and prevention (weather, wildfire, satellite, ICE, seismic, landslide, vegetation)	Benefits: With a high density of sensors, early hazard warning are more available and accurate. Limitations: Costly to achieve high sensor density. False alarms carry costs. Needs to be integrated into other operation systems.	8	In 2024, Austin Energy, a **US** utility, fully deployed an AI-driven wildfire-detection camera network across its 437-sq-mile service area. In 2024, Hawaiian Electric, a **US** utility, began installing a network of weather stations in high-risk areas.

Technology landscape: ensuring effective grid governance, interoperability and cybersecurity

Even the most advanced grid hardware cannot ensure resilience unless operators are able to deploy it quickly and correctly, and with protection against cyber-attacks. Operational resilience is an emerging area of digital innovation to ensure the effectiveness of all other hardware options described in this chapter, and the physical assets controlled by VPPs. The relevant technologies can be grouped according to whether they are for real-time monitoring, simulation or addressing cyber risks.

Growth of patenting in selected digital control technologies for grids, 2002-2022



Notes: SCADA = Supervisory Control and Data Acquisition. Each international patent family covers a single invention and includes patent applications filed and published at several patent offices. They are used here to provide a degree of control for patent quality.
Source: IEA and EPO (2024), Patents for Enhanced Electricity Grids.

Real-time system monitoring and situational awareness

It is increasingly complicated for grid operators to have visibility of what is happening on electricity networks from the transmission level down to the edge of the distribution system. In the past, when grids mostly operated in a single direction from centralised generators to consumers, and resources were less dynamic, the lack of real-time information across all assets was not a problem. Consequently, innovation efforts to collect, communicate and evaluate all the necessary information are relatively recent, with most tools emerging in the past decade or two. While they all have high potential for continual improvement and integration of AI support, the main tools are already at TRL 9.

Among mature technologies, **advanced distribution management systems** and **advanced energy management systems** – also used to manage flexibility (see above) – integrate data from smart meters, line sensors, and connected weather sensors to establish a detailed overview of local grid conditions. For example, TSOs and DSOs in storm-prone areas use pole-mounted vibration sensors and LiDAR weather radar to dynamically locate where lines might sway or sag dangerously. Wildfire monitoring networks – such as high-definition cameras and satellite-based fire detection – are being linked to grid **SCADA** systems or Wide-area Monitoring, Protection and Control Systems (WAMPAC) to allow pre-emptive re-routing. Interoperability standards for substation devices (IEC 61850), grid information (CIM) and distributed resources (IEEE 2030.5 / IEEE 1547) ensure that equipment from different vendors "speak the same language", reducing adoption costs.

Avenues of innovation for improved real-time system monitoring and situational awareness

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Smart meters (also known as advanced metering infrastructure)	Benefits: Smart meters give outage/voltage data to speed restoration and enable time-of-use customer pricing to incentivise VPPs. Limitations: Tight rules around consumer data protection. Most meters do not allow sub-second control.	9	Large-scale, over 50% penetration in many markets. In 2024, National Grid, a **US** grid utility, filed an advanced metering infrastructure report noting Field Area Network completion target in 2025 and meter rollout through 2027.
Energy management system (EMS)	Benefits: Control-room "brain" for the high-voltage grid and generation; keeps operations reliable and efficient. Limitations: Complex to set up and upgrade. Needs extensive cyber-security protection and operator training.	9	In 2025, CAISO, a **US** system operator, approved a major EMS hardware/software upgrade to enhance performance, robustness and security. In 2024, NESO, a **UK** system operator, highlighted the Advanced Dispatch Optimiser to modernise control-room operations with adaptive AI.
Interoperability standards	Benefits: Common "languages" let devices and platforms working together across vendors and regions, which is often not possible today. Limitations: Standards take time to update and can be incompatible with legacy systems.	9	In 2024, tools from Hitachi Energy, a **Swiss** equipment supplier, became the first certified under the new IEC 61850 programme. In 2024, the International Electrotechnical Commission (IEC), a global standards organisation, published Amendment 2 to the IEC 61850-6 standard, advancing machine-processable engineering and validation rules.
SCADA	Benefits: Brings field data to operators and sends safe remote commands. Speeds up bother incident detection and response. Limitations: Older versions are already lagging behind the newest technology in terms of speed and security.	9	In 2025, Oracle, a **US** software and equipment supplier, announced new ADMS/NMS capabilities to help operators manage distributed supplies and improve reliability in real time. In 2024, Survalent, a **Canadian** equipment supplier, introduced new tools that extend SCADA/OMS/DMS capabilities and field-crew mobile workflows. In 2025, GE Vernova and INESC TEC, a Portuguese research association, launched a project on zonal autonomous controls to resolve issues in smaller zones than SCADA.

Wide-area monitoring (including synchronised phasor measurement units and phasor data concentrators)	Benefits: High-speed time-synced measurements warn early of instability region-wide, enabling grid operators to respond. Limitations: Demanding in terms of communications, and data volumes. Visualisations and operator friendliness need improvements. Monitoring must be paired with a means of active response.	9	In 2024, PNNL, a **US** research institute, published open-source methods for PMU event analytics, frequency response and oscillation analysis. In 2025, CTU, an **Indian** TSO, issued PMU/WAMS communication and planning guidance embedded in the national ISTS rolling plan.

All these data streams flow into control centres that increasingly leverage big data analytics. AI can help filter the amounts of sensor data to pinpoint anomalies (e.g. a pattern of frequency fluctuations that precedes a blackout). Patent activity in AI for smart grids is growing briskly, targeting improved forecasting and real-time decision-making. The innovation challenge is ensuring interoperability and actionable information: merging legacy SCADA with new sensor platforms and presenting operators with clear insights rather than overwhelm. Progress is solid – for instance, Europe and North America now routinely use wide-area visualisation tools that display grid stress in real time. Further innovation will extend this situational awareness to the “prosumer” level, as millions of EVs, solar inverters, and batteries come online. In Japan, utilities are testing decentralised agent-based control where local controllers make split-second decisions based on neighbour status (a form of machine-speed awareness that could contain disturbances). Overall, maintaining reliable supply in a complex grid will depend on seeing problems before they cascade, and that hinges on pervasive sensing and intelligent analytics.

Digital twins and other advanced simulations

A digital twin is a virtual replica of the power grid that mirrors its state and can simulate its behaviour under various conditions. Grid operators are increasingly using digital twins and AI-powered decision support to evaluate scenarios and improve decisions, for example to study the impacts of adding new loads or supplies at a given node. Digital twins can include asset-level data to help predict failures, schedule maintenance or co-ordinate recovery from cyber-attacks. These allow planners and operators to virtually test upgrades or emergency actions before implementing them, saving time and avoiding mistakes. These tools stand at TRL 8 today, as they have not yet demonstrated accurate fidelity for modelling millions of connected loads and suppliers. However, innovation is motivated by potentially large pay-offs: the availability of a realistic simulator for training, a means of stress-testing regulatory change, and a detailed approach to automating emergency load shedding, would have high economic value.

In Singapore, a digital twin has been populated with real-time data from 18 000 transformers and 27 000 km of cables. In Australia, AEMO, a system operator, is developing a model that can test high-renewable grid behaviour. A Europe-wide digital twin for co-ordinated operational planning has been proposed. In the United Kingdom, National Grid, a TSO, is piloting a system-wide digital twin, while UK Power Networks, a DSO, works on asset-level twins to plan integration of new loads and supplies. Duke Energy, a grid operator, uses AI to predict storm-related outages and another, Exelon, uses AI for smarter voltage control. In 2022, Energinet, the Danish TSO, contracted Fugro, a technology company, to create a digital twin of its network and nearby vegetation to identify risks. Cloud-based grid platforms are making these tools affordable for smaller DSOs and grid operators in poorer regions.

Avenues of innovation for advanced grid simulation

Technology	Potential benefits and limitations	TRL	Examples of recent advances
AI decision support and operator tools	Benefits: With good quality data, outages can be predicted, risks can be identified, voltage can be maintained etc. Limitations: Data quality is critical. AI must be trusted without knowledge of its processing or visibility of data inputs. Can be a major culture change for grid operators. Needs periodic retraining.	8	In 2025, NESO, a **UK** system operator, and Alphabet's Tapestry, a **US** technology developer, launched the "Grand Optimiser project" to bring AI-assisted dispatch into the control room.
Cloud-based grid operations (light ADMS/ DERMS)	Benefits: Lower-costs are good for smaller TSOs and DSOs. Limitations: Carries higher cybersecurity risks.	9	In 2025, Oracle, a **US** software and equipment provider, announced new ADMS/NMS capabilities to manage DERs end-to-end, designed for cloud delivery. In 2024, **Norway** began deploying cloud-native grid orchestration software.
Grid digital twins (system and asset level)	Benefits: Can spot risks early and help co-ordinate upgrades. Can improve transparency between regulators and market participants. Limitations: Building and maintaining accurate models needs high quality detailed data, strong governance, and integration between different types of systems. Computing costs can be high.	8	In 2024, NESO, a **UK** system operator, funded a Wales system digital twin under the Powering Wales Renewably programme. In 2022, Endeavour Energy, an **Australian** utility, pioneered the use of engineering-grade network twins to mitigate weather risk.

Planning and interconnection study automation	Benefits: Faster and more consistent studies can alleviate grid connection queues. Limitations: Needs high quality data and models, as well as regulatory approvals, trust and culture changes.	8	In 2025, MISO, a **US** system operator, launched the ERAS fast-lane for qualifying projects, with quarterly automated studies through 2027.

Cybersecurity for grid control systems

The rapid digitalisation of power systems has brought cyber-attack risk to the forefront of grid governance. In response, innovation in grid cybersecurity tools and practices has evolved rapidly and many digital tools are now at TRL 9. They include advanced network intrusion detection systems tailored to SCADA protocols, AI-based anomaly detection that can scan millions of connected devices and distinguish a cyber-attack from routine equipment failures, and segmented network architectures that isolate critical control layers to prevent the breach from spreading. Iberdrola, a Spanish utility and DSO owner, and RWE, a German generator, have pilot projects in these areas.

Regulators are tightening rules for communications and requiring equipment to meet higher standards. For example, the EU Network Code on cybersecurity and the NIS Directive set out requirements for grid operators. Some government agencies have created platforms for sharing intelligence among grid operators for fast response of all companies to detected malware targeting a specific device type. However, security gaps remain where third-party devices – such as EV chargers and smart appliances – connect to the distribution grid. There is therefore a continual need for innovation in monitoring and detection of these "grid edge" devices and integration of compliant and updateable cybersecurity tools in all new equipment being connected.

Avenues of innovation for grid cybersecurity

Technology	Potential benefits and limitations	TRL	Examples of recent advances
Network segmentation and firewalls	Benefits: High level of security by preventing all but the most necessary data transfer between zones. Limitations: Needs clear standards, documentation and change control to ensure a balance of safety and continued operations.	9	In 2024, the **European Commission** published the first-ever Network Code on Cybersecurity for electricity, setting sector-specific minimum requirements for planning, monitoring, reporting and crisis management. In 2024, NIST, a **US** standards organisation, published Cybersecurity Framework 2.0, strengthening guidance on governance and supply-chain/identity controls that underpin zero-trust architectures.

SCADA and operational technology cybersecurity	Benefits: Protects the critical grid operating technology during cyber-attacks. Limitations: Can lock in dependencies on certain vendors. Legacy devices can limit overall effectiveness.	9	In 2024, GE Vernova and Dragos, a **US** cybersecurity supplier, teamed up to provide integrated OT cybersecurity services for electric utilities, combining grid automation with threat detection and incident response. In 2025, FERC, the **US** federal regulator, advanced Critical Infrastructure Protection standards to strengthen protections including communications management and supply-chain risk for BES cyber systems.
Security information and event management (SIEM)	Benefits: Provides a central “radar” for cyber threats. Supports compliance requirements and ex post investigations. Limitations: Needs constant availability of skilled analysts and good tuning to manage the “noise” of false alerts.	9	In 2024, ENISA, the **EU** cybersecurity agency, tested energy-sector cyber response, reinforcing SIEM/use-case tuning for sector operators. In 2025, the **US** government released the V-INT toolset, which integrates with commercial platforms to help utilities assess vulnerabilities and prioritise mitigations using live telemetry and threat intelligence.
Distributed resource cybersecurity	Benefits: Secures devices connected to distribution grids but not owned by DSOs (inverters, batteries, EV chargers) to prevent hijacking of VPPs. Limitations: Challenging to have a single system work across heterogenous models, vendors and owners.	7	In 2024, the **US** government proposed cybersecurity baselines for distribution systems and distributed resources to harmonise minimum protections across utilities. In 2025, NREL, a **US** research institute, contributed to a guide to cybersecurity for distributed resources interconnected with electric power systems (IEEE 1547.3).

Knowledge gaps to be filled

The avenues of innovation to enhance electricity grid resilience, as summarised in this chapter, demonstrate the breadth of effort around the world. Most of the technologies that are expected to play a significant role in ensuring reliable electricity supplies are already technically proven. However, knowledge gaps remain in several areas in relation to effective regulation and market design to reward investment in the most suitable technologies to prepare for emerging risks and ensure fast recovery from disruptions. There are also uncertainties about the optimal ways to use the technologies, how to demonstrate new approaches in real-world conditions on critical public infrastructure, and how to make the findings transferrable to a wide variety of grid contexts around the world.

Governance, data and cybersecurity for a highly digital grid

Data-rich grids are not automatically insight-rich. The range of technologies that collect and communicate data is expanding rapidly, including phasor measurement units, smart meters, line sensors, telemetry, weather and wildfire data. However, these are often siloed in incompatible models without embedded analytics that can inform operations in real-time. There is a lack of tools to turn large amounts of incoming data into actionable situational awareness during fast-moving events. While digital twins are promising for some applications, they are not yet widely available nor dependable for grid-wide decision-making across millions of items of connected equipment.

Cyber risk is a fast-moving area and knowledge about it will need to be improved and shared among grid operators encountering new situations. Few grid operators can update all their systems simultaneously, and there is a need for best practices for protecting internet-connected assets, sometimes owned by many different third parties, as well as assets connected to legacy operational technologies. Unless incident data and threat intelligence are shared regularly and workforces trained appropriately, this knowledge gap will remain.

System adequacy and coping with longer-duration supply-demand imbalances

Resource adequacy assessments often under-represent compound, long-lasting events, like heatwaves plus wildfires plus reduced transmission capacity, or multi-week periods of low output from nuclear, solar, wind or even fossil assets. Standard models are needed that can quantify these risks, the costs of grid restoration after disruptions, and the different technology options in terms of their impact on service to consumers. A widely-adopted set of resilience metrics that inform investment decisions or capacity auctions is lacking.

Technical knowledge gaps include a lack of agreement on how to evaluate the contribution that a heterogenous set of distributed small-scale assets can make to distribution grid flexibility and therefore resilience. While there have been improvements in the forecasting of how much demand-side resources will respond to request for flexibility, standard tools for verifying and adapting to forecast accuracy are needed, as well as appropriate rules for respecting feeder protection limits and safe islanding or reconnection of microgrids.

Future costs and expectations for LDES technologies that are just reaching pilot and demonstration stages – in terms of their efficiencies, performance degradation and replicability in different locations – are knowledge gaps that can be addressed with a portfolio of standardised tests in different countries.

System stability in inverter-dominated grids and HVDC grids

As synchronous machines retire, there is still no shared, operationally usable answer to how much grid-forming capability is needed, where, and in what form. Models of low-inertia dynamics, protection behaviour and control interactions differ across vendors, labs and TSOs, which makes it hard to compare studies or set clear performance requirements. Most pilots validate one grid-forming device at a time, meaning that there is a lack of multi-asset, multi-vendor examples of how fleets of batteries, wind plants, synchronous condensers and HVDC links can collectively cope with disturbances.

For HVDC, the bottleneck is moving from point-to-point "links" to multi-terminal, multi-vendor DC grids. Protection concepts, DC circuit breaker co-ordination and operating procedures for meshed offshore-onshore schemes are still immature. Breakers and cable joints exist, but standards and interoperability profiles that let different suppliers connect to the same DC grid are only starting to emerge, and manufacturing/installation capacity (e.g. slow jointing times) is a practical constraint.

Priorities for reaching the next innovation stages

This section focuses on a small number of recommendations to help governments, regulators, system operators, and other key grid service providers accelerate technology maturation and early adoption. Given the urgency of arising grid resilience challenges, the actions below are priorities for the next 5 years. They will require the involvement of a range of public and private actors so that effective standards, metrics and institutional arrangements establish the markets that will foster scale-up and optimisation. In many regions, more involvement of distribution-level operators, regulators and suppliers will be a central part of adapting to the changing nature of grid resilience.

Most of the technologies discussed in this chapter are already technically proven in a given context, including grid-forming inverters, synchronous condensers, HVDC, advanced conductors and VPPs, long-duration storage, dynamic ratings and self-healing automation. For these technologies, the next frontier is creating the rules, incentives and infrastructure at a system-wide level for these solutions to operate on complex grids and become routine. For other emerging technologies and nascent ideas, R&D funding and a clear path-to-market remain crucial.

- **Raise the incentives for grid operators and resource owners to adopt non-traditional technologies**. To shift from supporting individual technologies to incentivising deployment and integration, regulators should shift to paying for outcomes rather than narrow hardware functionalities. Performance-based regulation and procurement can focus on indicators of reliability under stress (e.g. duration and frequency of interruptions, load shedding, wildfire ignition risk) and specific system services, such as fast frequency response, inertia, voltage support, or black-start capability. A technology-neutral approach could encourage firms to invest in technologies like synchronous condensers at weak nodes, DLR on congested corridors, or island-capable mini-grids around critical loads. Market design and interconnection rules should also explicitly value advanced capabilities from batteries, wind and solar plants. They could allow and compensate grid-forming modes, create capacity or adequacy products for multi-day storage, and implement pay-for-performance contracts for demand response and VPPs. Integrated planning rules for the distribution system could place non-wire solutions – such as VPPs, storage and DLRs – on equal footing with traditional grid reinforcement. Public finance and guarantees could also underwrite first-of-a-kind projects, like large grid-forming batteries or regional VPPs, and ensure the projects share data and build reusable templates for future procurements.

- **Establish rules and environments to demonstrate technical effectiveness**. Advanced grid technologies need to be tested in controlled, real-world conditions to assess whether they can function safely in a specific system and its mix of assets, vendors and stresses. Regulatory sandboxes and other experimentation environments can enable this and test, for example, whether grid-forming batteries can provide frequency regulation, how mini-grids can be islanded and black-started, or how to operate multi-terminal HVDC configurations. However, regulatory sandboxes are only used by a small number of grid operators, leaving significant scope to expand them and share best practice. Sandboxes must also provide a pathway to further deployment after successful trials have been completed. Governments, TSOs and DSOs should require that large pilots share network models, test scripts, performance and disturbance reports, and all information that allows replication and comparison across manufacturers and countries. International initiatives can also curate common test cases to share lessons across countries, such as for low-inertia systems, grid-forming controls and DC protection schemes. Funding should prioritise multi-asset, multi-vendor demonstrations over single-device pilots, as interactions between devices and controls remain uncertain.
- **Develop widely used resilience metrics to inform investments, including for pilot projects.** This chapter shows that individual technologies to deliver a step-change in grid resilience are largely available. However, a common, outcome-based method for evaluating system-level resilience benefits – integrating restoration time, avoided outage durations and priority-load continuity – is missing. Metrics that can capture compound and long-duration events can inform R&D funding and governance, thereby providing the justification for these technologies in budgets and creating suitable incentives for innovators and private investors. Without them, more easily quantified traditional investments may continue to be prioritised, and innovations may stall at pilot stages. System operators, regulators

and governments should co-operate to establish definitions, test methods and reporting, and embed new metrics in procurement decisions and regulations.

- **Boost R&D, demonstration projects and international co-operation for early-stage and high-cost new technologies**. Over the next decade, several lower-TRL technologies need to be demonstrated as being feasible at scale, with clarity on lifetimes and how costs will decline, so that they can be adopted quickly once their economics improved. This requires both co-ordination and collaboration. Governments, TSOs, DSOs and manufacturers should co-ordinate R&D programmes around a set of flagship technology trials, aiming to achieve first-of-a-kind commercial projects and then bring down cost quickly afterwards. For example, a multi-terminal HVDC "backbone" for offshore wind, an urban superconducting cable corridor that unlocks dense load centres, or substation-scale solid-state transformers in areas with high levels of distributed supplies. Shared design reference cases, common testing protocols and aligned standards can keep costs down and bring lessons into planning tools across regions instead of isolated pilots. International initiatives could run competitive calls where multiple consortia tackle, for example, HVDC grid protection or lower-cost high-temperature superconducting equipment, with a commitment from participating system operators to adopt successful solutions in their next planning cycles.
- **Develop international standards and protocols for digital controls, forecasting, AI and data**. Increasingly digital grids will only support resilience if they exchange data reliably, securely, and in a form that operators trust. Standards bodies, regulators and utilities should prioritise harmonising a set of core data and communication standards and enforcing them via grid codes and procurement specifications: at the substation level, for exchanging network models, for integrating resources into the distribution grid, and agreed profiles for EV charging, smart meters and aggregator interfaces. Operators should define validation, monitoring and updating of machine-learning based forecasting, anomaly detection and asset-health models, as well as when and how outputs can be used and how they can be explained. Internationally shared benchmark datasets and reference problems can stimulate innovation and produce more comparable and broadly applicable results. One example could be open forecasting competitions for renewables or demand using real grid data. Regulators can also ensure cybersecurity is embedded in every interface definition, including those for aggregators and VPPs, through minimum cyber requirements for participation in flexibility markets or connection to the grid.
- **Tailor innovation efforts for countries with limited electricity access and resource-constrained grid operators**. Many grid operators in emerging market and developing economies have limited capital, weak utility balance sheets, and patchy basic infrastructure. International bodies, including multilateral banks, can use funding and capacity building to support the testing and adoption of innovative technologies in several areas. First, digital upgrades will improve planning and operations, even on fragile grids. Low-cost, digitally enabled governance tools such as geospatial network mapping, outage and asset-management systems,

and low-cost sensors on critical feeders enable better decision-making about where to site new supplies, large loads and minigrids. Second, assistance with scanning the market for appropriate technologies, plus R&D and pilot projects to adapt their implementation to local contexts. Technologies that are modular and replicable are likely to provide the most value, including standardised designs for island-capable mini-grids, or more advanced options like grid-forming inverters or long-duration storage. It may be possible to top-up financing for pilot projects to ensure that they support institutional learning as well as generalisable lessons for technical operation. Third, co-operation between grid operators will be valuable on pre-certification of control systems for smaller utilities and common regulations for grid extension and off-grid solutions together.

- **Agree innovation roadmaps to prepare for future grids with high shares of inverter-based resources**. Long-duration energy storage and seasonal storage technologies require further technical development and testing of competing designs among those that can operate cost-effectively over 10-100 hours or more. This should be a priority for governments anticipating future high shares of variable renewable electricity supplies or long, weather-related disruptions, for example to hydropower. On the demand side, the focus should be on scaling VPPs alongside pay-for-performance telemetry, cybersecurity features and standardised device certification for aggregators to deliver firm, auditable megawatts. Innovation that can unlock greater grid capacity without building new infrastructure is a third priority, including dynamic line rating, advanced conductors and topology optimisation, self-healing automation (FLISR) and advanced data-driven voltage control. Grid operators need new protocols not only for new technologies, but also how to enable multiple vendors to operate on networks that include legacy assets, requiring common models, test scripts and procurement specifications.

Chapter 7. Focus: Innovation to make gigawatts of grid-connected fusion energy a reality

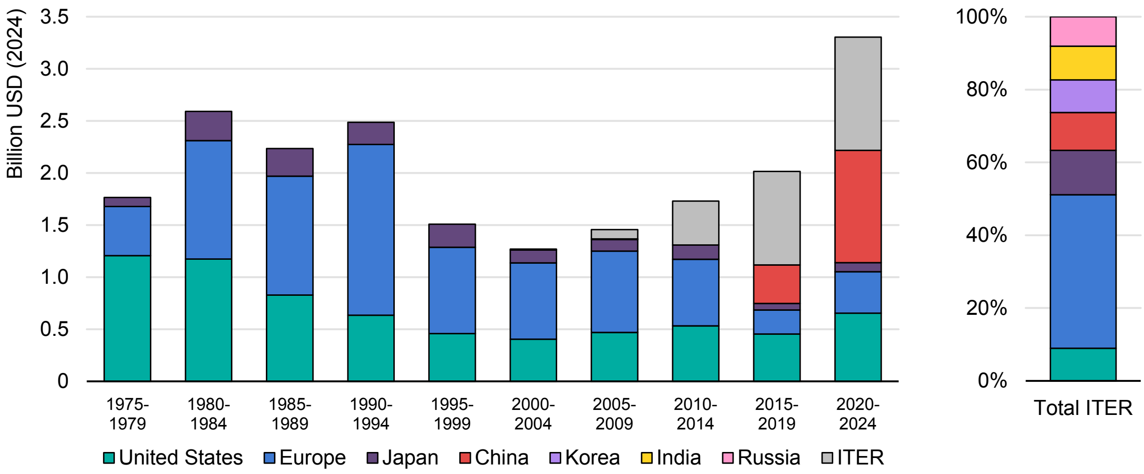
Fusion energy has been making headlines recently. In 2025, in Germany, a steady-state high-confinement plasma was maintained above key density and temperature thresholds using magnetic forces for more than 40 seconds. This followed shortly after a similar record set in the United Kingdom 2 years before. In parallel, longer records for plasma duration below this threshold were broken twice in early 2025, passing 18 minutes in China and then 22 minutes in France. Using a laser-based approach, researchers in the United States recorded net energy output several times, including in 2025. All of these advances took place in government-owned research facilities.

Fusion energy has also recently attracted interest from the private sector, where fusion technology pioneers are raising unprecedented levels of venture capital (VC) funding. Even if it is a long shot, a successful fusion power plant design could revolutionise the energy system, providing high and constant power output and spinning inertia for grid stabilisation, minimal high-level radioactive waste and no CO_2 emissions, without the need for scarce fuel inputs. Once ignited, the reaction in a grid-scale power plant could potentially be sustained with modest fuel inputs – for example, less than five tonnes of lithium and several thousand tonnes of water per year – for as many years as the reactor can remain operational.

This chapter explains fusion technologies so that non-experts can understand the state of innovation and the key challenges in this area. After describing different technological approaches, to help put examples of recent progress in context, it concludes by outlining several knowledge gaps and priority actions for realising the first grid-connected plants, in line with national roadmaps. A key feature of fusion energy R&D is that several major outstanding challenges – including developing new materials and cost-effective fuel production – must be tackled simultaneously before they can contribute to complex and costly engineering projects. To date, the largest projects have been made possible by extensive international co-operation.

Excitement about fusion energy is not new: it has been portrayed as the energy source of the future ever since it was first proposed in the 1950s. Since the mid-1970s, around USD 100 billion (in 2024 USD) has been spent by governments around the world on fusion energy R&D. Due to the high costs and risks of each experiment, this funding has been spent with a much higher level of international co-operation than for any other area of energy innovation. The IEA Fusion Power Coordinating Committee was established in 1975 to oversee a variety of activities on fusion among IEA Members. These efforts have led to a variety of very sophisticated test facilities for conditions that could lead to the controlled fusion of atomic nuclei. Building and operating these reactors – mainly in the United States, Japan, United Kingdom, Germany, France, Russia and, more recently, China – has led to advances in the state-of-the-art of fusion energy related plasma physics.

Estimated annual average public R&D funding for fusion energy, 1975-2024



Notes: ITER is an experimental reactor located in France that has been designed to prove the commercial feasibility of fusion energy. Data shown are attributed to energy-related research in public sources. Due to certain overlaps between civil and military research, for example in relation to thermonuclear ignition, the chart likely underestimates total relevant funding. ITER budgets are calculated based on the organisation's financial reports, which use a narrower scope than governments in their reporting of ITER-related funding. Spending by countries not shown can be assumed to be small, excepting their contributions to the ITER budget.
Sources: IEA Energy Technology RD&D budgets database, accessed in January 2026, and ITER and other national reports.

However, while some of the experiments have demonstrated successful fusion for brief periods, no facility has been able to generate more heat energy output than energy put into it. None of the experiments have been hooked up to a generator to produce electricity from the output heat. In fact, many of the experiments have identified additional scientific and engineering challenges to be overcome before a dependable fusion energy plant can be designed.

In 2025, several major governments announced commitments to commercialising fusion energy as quickly as possible. The rhetoric has noticeably shifted towards a race to the first power plants.

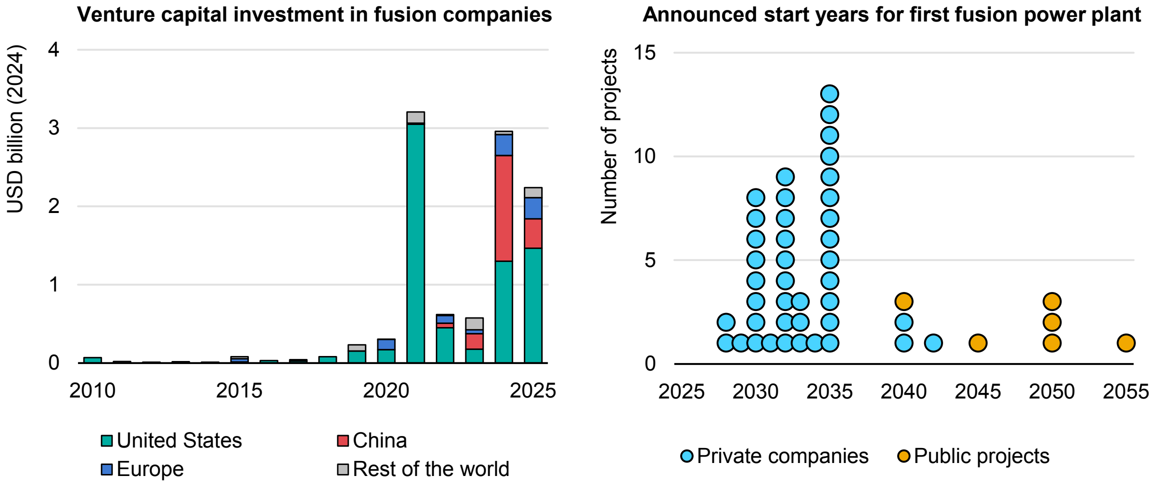
- In June 2025, as part of its new Clean Energy Industries Sector Plan, the United Kingdom announced the equivalent of USD 3.2 billion for a 5-year period in pursuit of a prototype fusion powerplant by 2040.

- In June 2025, Japan updated its Fusion Energy Innovation Strategy, which aims to demonstrate power generation in the 2030s via public-private partnerships.
- In July 2025, China established a state-owned fusion energy company as a subsidiary of the China National Nuclear Corporation, with around USD 1.6 billion of initial capital. Then, in November 2025, China signed an agreement with representatives of research institutes in more than 10 countries, mostly European, to continue sharing knowledge, in particular in relation to China's under-construction "BEST" reactor, which it hopes will demonstrate net energy earlier than any comparable major projects.
- In October 2025, the US government published a fusion energy roadmap, with the goal of aligning public investment and private innovation to deliver commercial fusion power to the grid by the mid-2030s.
- In October 2025, Germany published an action plan committing to spend more than the equivalent of USD 2.2 billion on fusion research and projects by 2029.
- In January 2026, Korea doubled its annual fusion R&D spending, allocating the equivalent of USD 82 million in 2026 towards a demonstration reactor by 2035.

These governments – plus India, Russia and other European countries – already collaborate on the ITER project. The project was launched in 1986, and in 2006 became an international institution with a mandate to build a facility in France that proves the viability of fusion energy in the 2040s. The advanced experimental reactors in operation around the world today serve as inputs to the design of ITER, which entered construction in 2010. Through ITER, public funding outside the United States has increased significantly, and consortium members have been able to plan for larger post-ITER projects.

Optimism has also surged in the private sector and – for the first time – private finance is complementing public funds. VC investors are willing to put their money at risk because they have been persuaded that researchers will soon be making technological advances that have real-world commercial value. In 2025, Google and Microsoft – companies that need electricity to power their artificial intelligence businesses – became the first to take out contracts for the future output of unbuilt fusion power plants that have not yet been fully designed or funded. The developers – whose projects largely build on government-funded programmes – claim that they will be able to bring such plants online within 10 years, a claim that seemed inconceivable just one decade ago.

Global venture capital funding for fusion companies, 2010-2025, and announced start years for electricity-generating fusion plants, 2025-2055



Note: Venture capital investment in 2025 only covers the period until August 2025.
Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

The case for strengthened innovation

There continues to be broad consensus among governments and analysts that the promise of fusion energy is both technically feasible and worth pursuing. While issues of regulation, remuneration and public support will doubtless arise in the future – regulations have already been clarified in the United States and United Kingdom – the near-term challenges relate to technology innovation. As innovators seek to scale up a range of different approaches at larger scales, the scope of fusion innovation is broadening. In addition to questions of fundamental science, engineering problems – such as the serial production of magnets, material durability and low-cost fuel supplies – are coming into sharp focus.

For there to be investments in commercial-scale fusion power plants in the future, a range of technology areas must be advanced simultaneously. Where possible, combining the best outcomes in each area will provide the greatest chance of compressing the timeline. To date, fusion energy research has been notable for high levels of collaboration between public programmes, companies and different countries, which will continue to be essential through the next stages of testing and scale-up.

Fusion energy terminology: a primer

The complex science and terminology of fusion energy is a barrier to understanding by non-experts and contributes to misunderstandings about the status and progress of the technology. The distinctions between announcements about "ignition", "plasma confinement" or different reactor types are hard to place in context without knowledge of the physics. To help non-experts, some of the key concepts are explained here and in boxes in subsequent sections.

- **Fusion**. A nuclear reaction in which light atomic nuclei are forced together to form a larger particle and release energy, usually in the form of neutrons with high kinetic energy that can be used to generate heat. In stars like the Sun, immense gravitational pressure and high temperatures enable hydrogen nuclei to overcome their electrostatic repulsion and fuse together.
- **Plasma.** Under the pressures and temperature conditions reached in fusion reactors, fuel is in a non-gaseous, non-liquid state of matter called a plasma, in which electrons separate and become free from their atomic nuclei. Plasmas conduct electricity, and their particles move collectively in waves. Under the extreme conditions of fusion reactions, plasmas are unstable, making it difficult to control them so that the energy remains in the intended reaction location. The Sun is almost entirely composed of plasma that supports the fusion reaction that generates its heat.
- **Plasma confinement system.** The central component of most fusion reactors, which are industrial installations that can replicate fusion reactions on Earth, without the gravity of a star to heat and compress the fuel into plasma. These systems must confine a sufficiently hot and dense plasma for a sufficiently long time in a vacuum to generate fusion without using more energy for trapping and controlling the plasma than the energy produced by fusion. The science and engineering of plasma confinement represent the biggest challenges for fusion.
- **Plasma energy breakeven.** The point at which the energy output from a fusion reaction is equal to the energy input to the reaction as heat, pressure and electromagnetic energy. This is denoted as Q=1. It does not include the energy inputs prior to the reaction itself, such as electricity to power magnets or to charge lasers, which can be much greater than the energy transferred to the plasma.
- **Ignition.** The point at which the heat from a nuclear fusion reaction is sufficient to heat the continuation of the reaction without external heat sources. After ignition, a fusion reaction is thermally self-sustaining. Ignition may start to occur at Q=5 in some devices, with Q rising higher after the ignition point.

- **Triple product.** A combination of plasma density, temperature and plasma confinement duration metrics. The triple product must exceed a threshold called the Lawson Criterion before ignition is possible.
- **Engineering breakeven**. The point at which the energy output of the fusion reaction is equal to all the energy inputs to produce the fuel, sustain the fusion reaction and operate the plant. To account for all energy inputs, Q=10 or more may be required.
- **Deuterium-tritium fuel**. The fuel combination that is generally considered most promising for commercial fusion energy. While much fusion research to date has focused on deuterium fuel for simplicity and cost reasons, there is broad agreement that the deuterium-deuterium reaction will not be the one that supports commercialisation of fusion energy. Other nuclear fuel reaction options include proton-boron, but most attention is on fusing tritium with deuterium, which releases nearly six times as much energy as the deuterium-only reaction. The larger size of tritium compared with deuterium makes fusion reactions in the plasma more likely.
- **Deuterium**. Deuterium is an isotope of hydrogen that has one neutron, and it is stable and therefore not radioactive. As it is naturally present in in a non-negligible proportion within hydrogen atoms, it can be produced by separating heavier water molecules from lighter ones, which is already done industrially, for example in heavy water-moderated nuclear reactors. Most existing experimental work fuses two deuterium atoms.
- **Tritium**. Tritium is an isotope of hydrogen that has two neutrons. It is much more expensive to produce than deuterium and cannot be found in natural deposits. It is radioactive, with a half-life of 12 years and, while the helium that is the product of deuterium-tritium fusion is not radioactive, the materials with which tritium comes into contact are made radioactive by neutrons from the reaction and must be handled appropriately. Tritium is already available for commercial uses and is well understood by radiological regulators.

Most innovation effort today is directed at different technological approaches to confining plasma. Three main approaches have already been proven to be controllable in large laboratory experiments, for which research infrastructure can cost in excess of USD 500 million. Each approach is being actively pursued by research teams around the world, typically involving international co-operation.

- **Magnetic confinement.** This approach relies on long reaction times and low plasma densities to achieve ignition. Extremely powerful magnetic fields hold the plasma in place so that it does not touch the walls of the vacuum chamber; no reactor material could withstand the temperatures if it were to touch. The plasma must be pre-heated and then maintained in a stable condition. A major challenge is to prevent instabilities and turbulence in the plasma that would make the fusion reaction impossible. Tokamaks and stellarators are both types of magnetic confinement.

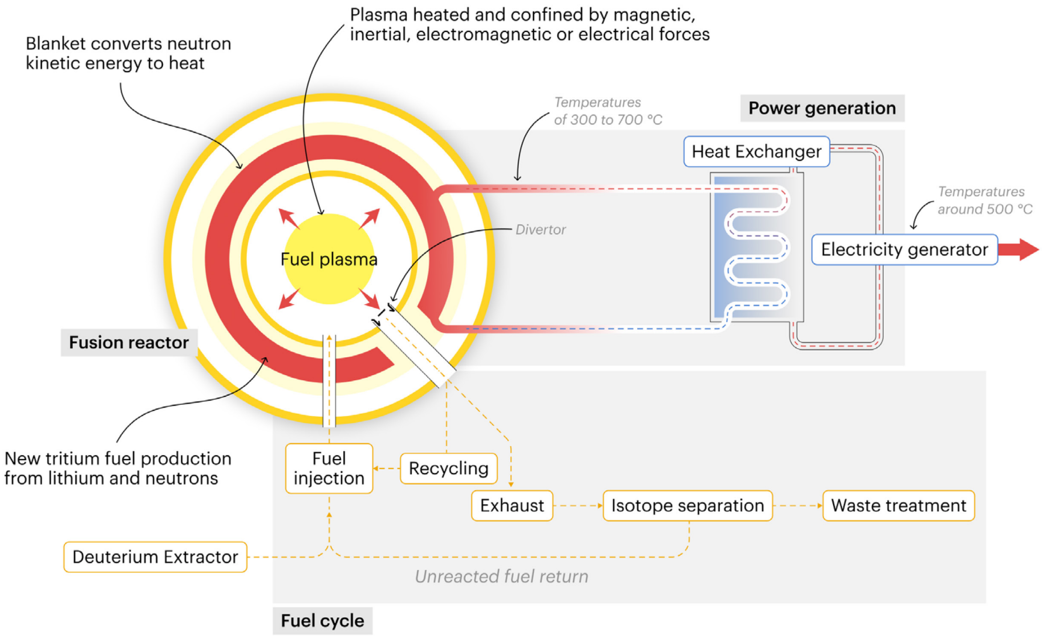
- **Inertial confinement.** An approach that relies on extremely short reaction times, but with very high plasma densities. Generally, lasers are used to rapidly compress and heat a small fuel pellet, causing the outer layer to explode and the inner core to reach extreme temperatures and pressures, releasing large amounts of pulsed nuclear energy. Individual fusion reactions are short, each requiring a new fuel pellet and releasing energy momentarily.
- **Magneto-inertial confinement.** This third approach splits the difference between inertial and magnetic confinement and relies on intermediate reaction times and plasma densities. By using magnetic fields to increase heat and compression, performance could exceed that of inertial confinement (which is hard to reproduce continually and has high energy requirements) and magnetic confinement (which is hard to self-sustain for sufficient energy production). Although promising, this approach has not yet demonstrated results at a similar level to the other two.

Within each of these approaches, there are competing designs for the reactor and fuel, as well as other operational differences. As described in the following sections, these different designs all have advantages and disadvantages, and have achieved different technology readiness levels (TRLs) to date.

In addition to the three main approaches, others are in development at lower TRL levels in research institutes and start-ups around the world. These are mainly modifications to designs that were first proposed in the scientific literature many decades ago. Today, these other approaches would appear to be long shots to win the race to gigawatts of deployment. Some innovators have raised limited funds in recent years to continue work on electrostatic confinement, electrical discharge confinement or muon-catalysed fusion, for which progress has often disappointed.

Aside from plasma confinement, there are significant innovation needs for integrating the confinement system into a larger facility that can provide a continual fuel supply, capture the energy produced and convert it to useful outputs, such as electricity. Many of these components need not be specific to a particular confinement approach but, given the state of plasma confinement demonstration, these integration technologies have not yet been extensively designed or optimised.

The main technology elements to be combined in a future fusion energy power plant



Technology readiness and steps on the way to commercial fusion energy

Assigning a technology readiness level (TRL) to any of the approaches to fusion energy is difficult compared with other energy technologies. Using the IEA's approach, TRL is assessed based on the technology's journey from a concept (TRL 1) to the marketing of a product or process to customers for the provision of energy, for example electricity, with technology guarantees (TRL 9). The closer a given confinement approach gets to TRL 9, the more ancillary equipment will be added to each reactor installation, until the addition of the power generation cycle.

In the IEA's view, several approaches to plasma confinement stand at TRL 3, defined as "experimental proof of concept for separate technology components". TRL 4 involves "laboratory-validated technology (integrated components) in a non-representative setting". The validation that would be sufficient for TRL 4 is continuous operation with plasma energy breakeven for a short period. For magnetic confinement, a period of 10 minutes could be reasonable. For inertial or magneto-inertial confinement, a high enough frequency of "shots" would be needed, perhaps one every 10 seconds. None of the technologies have yet reached TRL 4, despite inertial confinement having reached ignition in 2022.

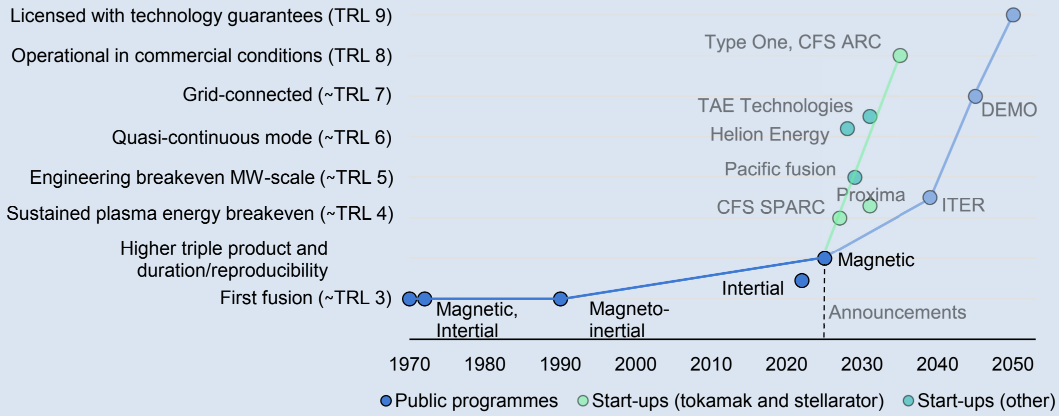
Nonetheless, the approaches are at different levels of maturity and can be distinguished from one another by looking at the sequence of steps through which they each must pass if successful. So far, the approaches that have achieved the highest levels of maturity are from international, government-backed experimental projects operated in support of the under-construction ITER project and its potential national successors. The plans of several start-ups aim to eclipse the pace of progress of these public projects and to have grid-connected demonstration projects online in the 2030s with smaller budgets. Four start-ups (all US-based) that have declared such plans have collectively raised USD 6 billion in equity since 2015.

The key steps for each approach are outlined below:

- Prove experimentally that the confinement system can produce fusion (TRL 3). This was achieved in 1968 for magnetic confinement (tokamak), 1972 for inertial confinement and by the 2000s for some magneto-inertial devices.
- Demonstrate high triple product values for long enough (or reproducibly enough) to justify investment in a multi-megawatt pilot plant with design features closer to a commercial plant. This was achieved in 2025 (tokamak and stellarator) in government-owned laboratories, and Commonwealth Fusion Systems, a start-up, aims to achieve this in 2027. Whether or not these projects, or the ITER project, achieve TRL 4 in the IEA scale depends on duration or frequency of operation.
- Operate a reactor at the 1 MW_{th} to 100 MW_{th} scale with engineering breakeven for periods of at least 10 minutes (TRL 5). Public roadmaps mostly target this milestone in the 2040s.
- Operate a reactor with engineering breakeven in quasi-continuous mode in such a way that the energy output could be converted to electricity (TRL 6 and TRL 7). Some start-ups claim they can achieve this by 2028 (Helion), or the early 2030s (Commonwealth Fusion Systems and TAE Technologies, for example).
- Demonstrate sustained operation of a reactor integrated into a facility that produces electricity or another saleable energy output at a marketable scale (TRL 8 to TRL 9). Public roadmaps typically set this target for the 2040s or 2050s. Analysts have suggested that USD 8 000 per kilowatt is a reasonable target for a new plant’s capital costs by 2050, then half of that value by 2100.

At each stage, more attention is paid to the standardisation of design, operation and fuel production. Designs that allow key components to be produced repeatedly at lower cost with higher durability, and ability to be serviced or replaced, will be of critical importance at higher TRL.

Stages of fusion energy development to date, and announced future milestones for public and private sector projects



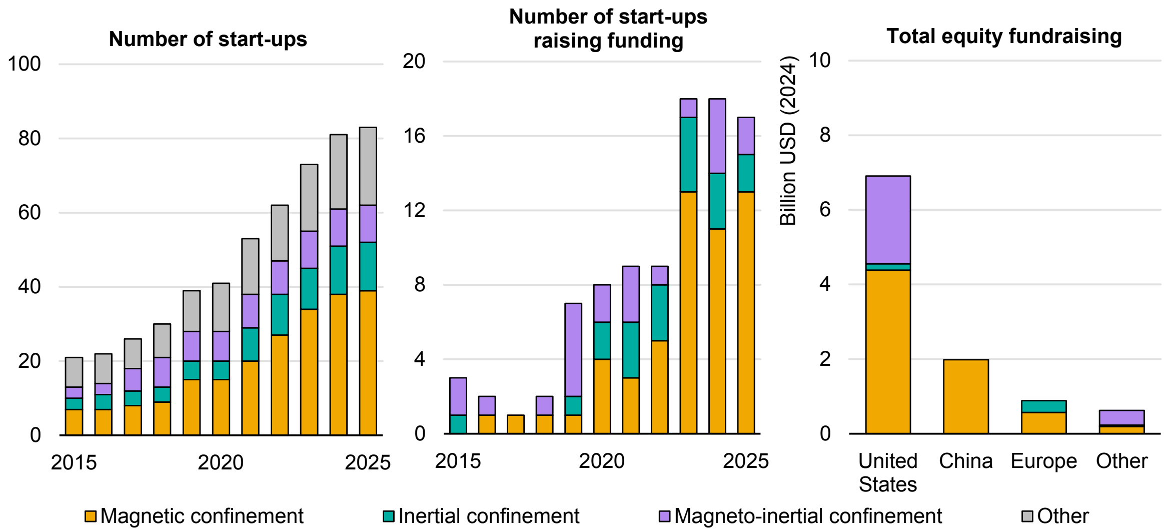
Notes: TRL = technology readiness level. CFS SPARC and CFS ARC are projects of the Commonwealth Fusion Systems company. ITER is a project funded by an intergovernmental consortium. DEMO refers to a set of proposed projects by governments as successors to ITER. TRL values are given as illustrative but may not be match the stages precisely.

Technology landscape: plasma confinement

Approaches to plasma confinement are diversifying again. The early decades of fusion energy research were characterised by work on a range of different approaches, most of which was largely theoretical. From the 1990s, large public research programmes consolidated around a few major experiments with magnetic confinement (tokamaks) and an inertial confinement facility in the United States. With the advent of funding available to spin-off companies in the past decade, a range of technologies – both the modification of more advanced approaches as well as previously untested approaches – are being pursued by teams around the world. In addition, some start-ups are dedicated to the development of higher performance, manufacturable and more cost-effective individual components for the most advanced approaches. The wider range of funded research on different engineering challenges is spurring faster innovation.

While public research projects continue to lead the way in terms of experimental maturity, there are now more than 80 fusion energy start-ups, up from 20 just 10 years ago. Some aim to be quicker than the public institutes at building expensive operational demonstration plants, thanks to their commercial mindset, while others hope to become suppliers of the cheapest or most effective equipment and services. In total, these start-ups have raised USD 10 billion since 2020, with almost 40 raising more than USD 10 million each. This is over 5% of all energy VC funding over the same period. For comparison, AI start-ups have raised USD 300 billion since 2020. Most of the VC capital for fusion has been directed to start-ups developing magnetic confinement, especially in the United States. There is more geographical diversity among the 40 start-ups working on other approaches or the fuel cycle, the majority of which have yet to raise equity.

Number of fusion energy start-ups, number of start-ups raising funding, and equity fundraising by region, by confinement approach, 2015-2025



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

Magnetic confinement

Magnetic confinement is currently the most advanced approach to fusion energy, due to the progress with two design types – tokamaks and stellarators – which account for most of the public funding. Their outlook has been brightened by recent developments for producing high-temperature superconducting magnets.

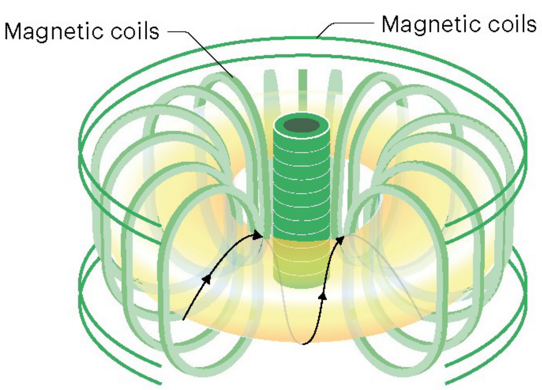
Magnetic confinement terminology

- **Tokamak.** A toroidal (doughnut-shaped) chamber composed of powerful magnetic coils that generate a circular magnetic field to guide plasma around the circular track of the toroid. Additional magnets in the centre and around the toroid create an electrical current in the plasma that prevents it from drifting towards the chamber walls.
- **Stellarator.** Has the shape of a twisted doughnut, which directly generates the desired magnetic field, without needing to create an electrical current within the plasma. Advances in computational design and magnets are allowing

stellarators to approach the performance of tokamaks, which supplanted them due to engineering challenges in the early days of fusion research.

- **Magnetic field strength (tesla)**. The force exerted by a magnetic field on electrical systems. To hold the plasma within a defined trajectory, magnetic fields generally need to be around 5 to 20 tesla. For comparison, the magnets used in wind turbines or for lifting scrap cars have strengths of around one tesla, though magnets of more than 40 tesla have been built experimentally.
- **High-temperature superconductor**. Conductors without electrical resistance at temperatures higher than those of “conventional” superconductors, typically higher than the boiling point of liquid nitrogen (-196°C). Magnets made with high-temperature superconductors can also be operated at colder temperatures, at which they generate stronger magnetic fields than other superconductors, allowing designers to optimise cooling costs and magnet strength. Magnet strength influences the size and efficiency of a fusion reactor.
- **H-mode**. A high-confinement plasma regime where turbulence at the edge is suppressed, forming a transport barrier that greatly improves energy retention. It enables sustained, high-performance operation essential for steady-state fusion reactors, with higher stability, and confinement efficiency.
- **(Breeding) blanket**. A system within the fusion reactor structure that converts kinetic energy from neutron bombardment into thermal energy Magnetic confinement, which requires fuel to be constantly available to the reactor is expected to use the blanket as a tritium “breeder”, by containing lithium that is converted by the neutrons into tritium and helium. The reactor can thereby self-produce tritium fuel as long as lithium is supplied.

The state of tokamak innovation



Around 50 tokamaks have now been built in experimental settings around the world, and 17 other devices are planned or under construction, sometimes with expected commercial applications. Many major scientific challenges have been overcome and records for plasma confinement broken. Most recently, the maintained steady-state high-confinement plasma operation record was set at 17 minutes and 46 seconds at the EAST reactor in **China** in January 2025, and then at 22 minutes and 17 seconds at the WEST reactor in **France** in February 2025. These reactors have heating inputs of 7 MW and 17 MW, respectively, and are not designed to produce fusion energy output, but rather to test very specific parameters, configurations or materials that will have potential applications in prototype or commercial reactors. Q factors were therefore very low during these experiments.

Tokamaks have already demonstrated fusion energy output, but not plasma energy breakeven. The Tokamak Fusion Test Reactor in the **United States** produced over 10 MW of fusion power with Q=0.2 for less than 1 second in 1994, and 3 years later, the Joint European Torus in the **United Kingdom** achieved Q=0.67 and 16 MW. In 2024, shortly before it was decommissioned, the same UK plant set a new record, producing 0.02 MWh of heat with a 6-second pulse and reached record triple product values for minute-long pulses. In China, a 20 MW tokamak is under construction and scheduled to start experiments in 2027 with the aim of achieving Q=1 with deuterium-tritium fuel thereafter.

The international ITER project is supported by a wide range of experiments conducted on dozens of public experimental devices. These are designed to inform an under-construction tokamak in France that is expected by many to be the first TRL 4 tokamak, by 2040. ITER is funded and operated by China, the European Union, India, Japan, Russia, Korea and the United States. It is designed to be much larger than existing tokamaks and to generate fusion energy of 500 MW thermal for up to 600 seconds at a time, if the target of Q=10 is achieved. ITER has suffered various setbacks and delays, pushing its planned Q=10 date back to 2039. Its 2010-2024 budget, estimated at USD 12 billion, represents more than 30% of the global public R&D budget destined for fusion during the same period.[29]

Demonstration projects that deliver continuous electricity by achieving self-sufficient tritium breeding and large net power (Q ≈ 30-50, TRL 7) are being planned for 2050 by ITER member governments. They will use ITER-derived knowledge to test full engineering systems. In July 2025, the Chinese government sold just under 50% of China Fusion Company, previously a subsidiary of the state-owned China National Nuclear Corporation, to six other companies that are also mostly government-led. This consolidation and investment strategy has created a tokamak-focused company worth around USD 1.6 billion dollars.

Advances in the development of high-temperature superconducting magnets have helped make it possible for the private sector to build its own tokamaks. Three start-ups – Commonwealth Fusion Systems in the United States, Tokamak Energy in the United Kingdom and Energy Singularity in China – have collectively raised USD 4 billion in equity. Of these, Commonwealth Fusion Systems aims to have its

[29] This value represents the budget reported by ITER, which may not include all government activities in support of ITER within its scope.

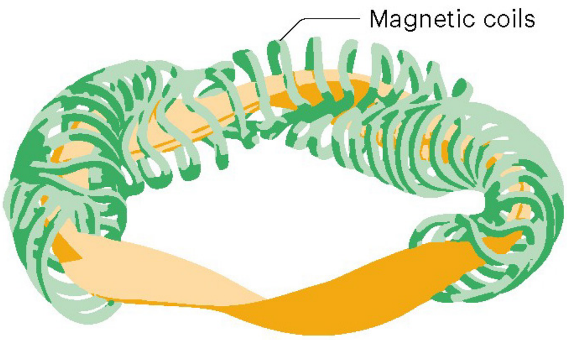
under-construction demonstrator achieve net energy by 2027.The company aims to proceed to a grid-connected power plant in the early 2030s, for which it received permits in 2025. The other two firms, which are developing a different (spherical) reactor shape, aim to operate their pilots by 2030 or shortly thereafter.

Spherical tokamaks

The type of tokamak that has been tested most has a large aspect ratio, i.e. a wide torus tube, shaped like a doughnut. Spherical Tokamaks are different: they are shaped more like a cored apple. This design could allow higher plasma pressure and therefore more fusion power for a given magnetic field strength and, potentially, lower construction costs. However, the limited central column space requires alternative superconductor designs and limits the ability to use neutron shielding and include tritium breeding. In addition, the intense heat at the central column may degrade materials faster.

In 2025, the **United Kingdom** announced USD 3.2 billion in funding for 2025-2030, mainly for a consortium (called STEP) to work towards a 100 MW_e spherical tokamak prototype by 2040. In China, ENN Group, a private **Chinese** company, has begun operating a spherical torus and achieved plasma with boron as a fuel. It is designing a larger machine to supply 17 MW of heat by 2028. Tokamak Energy, a spin-off from the UK Atomic Energy Authority, and Startorus Fusion, a Chinese start-up, are working on the use of high-temperature superconducting magnets to further develop this approach. Recently, Tokamak Energy reported the highest temperature (in 2023) and triple product (2025) to date for a spherical tokamak. Startorus Fusion, which raised USD 143 million in early 2026, is exploring so-called negative triangularity (a variation of the torus shape) to reduce plasma instabilities. In December 2024, it reported that it was ready to begin constructing the world's first negative triangularity tokamak once permits were received, employing a high-temperature superconducting tape developed and tested with Shanghai Superconductor Technology, a company backed by government funds. This approach is also being pioneered by the University of Seville, a public university in Spain, which achieved its first plasma with a spherical device in 2025.

The state of stellarator innovation



In 2023, the Wendelstein 7-X stellarator, built and operated by the public Max Planck Institute for Plasma Physics in **Germany**, achieved a long-pulse discharge of eight minutes with high energy turnover and in 2025, it set a world record for stellarator triple product. Completed in 2015, it is the world's largest quasi-isodynamic stellarator and the recipient of over USD 1.5 billion from Germany and the **European Union**. Another reactor, **Japan**'s Large Helical Device (LHD), was completed in 1998 and achieved long plasma discharges in 2014. it holds the record for the highest temperature achieved by a helical device. In 2025, it achieved a significant improvement in component design, improving the efficiency of a critical plasma measurement tool. Helical devices use comparatively simple geometries and are regarded as the simplest class of stellarator configurations.

The Wendelstein 7-X and the LHD are designed to demonstrate plasma confinement using thermal inputs of 10-15 MW. They are not designed to use deuterium-tritium fuel or demonstrate fusion energy output, which would require higher temperatures and plasma densities. However, their experimental results are a basis for designing commercial stellarator reactors with modified principles, something now being pursued by several start-ups, most of which are working on systems closer in design to Wendelstein 7-X.

Type One Energy, a spin-off from a **US** public university, is designing a 350 MW demonstration project, for which it has raised around USD 80 million in equity and is in discussion with a utility about potential power purchases. The firm is exploring licensing of high-temperature superconducting magnets from Commonwealth Fusion Systems. In May 2025, a concept for a quasi-isodynamic stellarator was published by an international team of researchers, including from Proxima Fusion, a spin-off from publicly funded German research that has raised USD 200 million in equity since 2023. Proxima Fusion has announced a partnership with Europe's public sector co-ordinator of fusion research to scale up the idea to an operational demonstration stellarator in 2031, and aims to use AI simulations to speed up the pace of development. In March 2025, Renaissance Fusion, a **French** start-up, raised USD 34 million in equity to design a reactor based on its intellectual property related to superconducting magnets and liquid wall materials developed in publicly funded research. In January 2024, Gauss Fusion, a public-private joint venture between **European** companies and governments, selected this design for its project to build a pilot plant by 2045.

A feature of stellarator research for many decades has been the challenge of controlling the movement of particles, the fundamental drift of which leads to energy loss. This problem almost brought research to a halt between the 1960s and early 2000s. Recent advances in computing have allowed designs to be improved significantly, largely solving the issue, but there are remaining challenges with plasma turbulence, the cost of achieving acceptable efficiencies, durability, and the management of exhaust particles and heat .

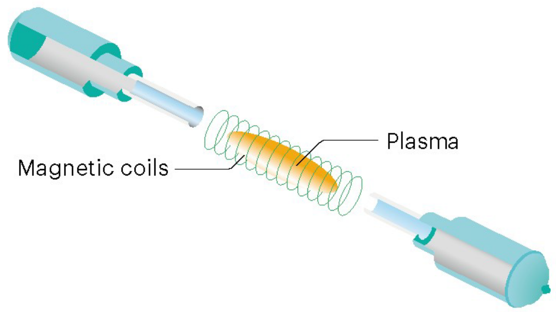
The state of high-temperature superconducting magnet innovation

Magnetic confinement approaches to fusion energy require very strong magnetic fields that can only be sustained with superconducting wires and cables. While it has been possible since the 1990s to make superconducting materials that can transmit the necessary current density at temperatures higher than that of liquid nitrogen, most fusion experiments have used conventional lower-temperature superconductors that cannot deliver the same magnetic field strength. This is a problem for building large-scale effective tokamaks or stellarators, which need to be based on industrially producible, compact components, and to reduce the energy efficiency trade-off between magnetic field strength and energy inputs.

Significant advances in high-temperature superconducting magnets are the product of recent work on solving engineering challenges for future fusion energy scale-up. This is a departure from decades of research focused on building experiments to test theories and demonstrate feasibility. Magnets that can be manufactured in bulk are a prerequisite for scale-up and, if this engineering challenge were only to be tackled after the achievement of Q=10 in experimental conditions, then the time horizon for achieving commercial deployment would remain many decades away. Instead, the availability of more affordable high-temperature superconducting magnets in the near future could quicken the pace of fusion development, especially among private firms that can purchase them. By integrating high-temperature superconducting magnets in proven reactor designs, they could be made more compact, with lower capital and operating costs. Even though these reactors may have shorter lifespans, they will be key to gaining operational experience.

Commonwealth Fusion Systems has worked with the Massachusetts Institute of Technology to manufacture high-temperature superconducting cables and magnets in larger quantities and with reliable quality. As a cable, the material is flexible and can be shaped into complex designs for optimising plasma confinement and cut to size. In addition to developing its own reactor, Commonwealth Fusion Systems has become a supplier of superconducting cables and magnets to other developers of fusion reactors. In addition, work on fusion energy has enabled progress towards the wider adoption of superconductors in the electricity system, including for meeting the space constraints for cables in data centres. In March 2025, Energy Singularity reported achieving 21.7 tesla with its tokamak magnet. In 2025, Tokamak Energy used its in-house magnets to generate over 10 tesla and aims to commercialise this technology.

The state of innovation for other magnetic confinement approaches



Another pathway for magnetic confinement fusion would be to exploit specific plasma configurations, named Field-Reversed Configurations (FRCs), where the plasma self-confines. By using the magnetic field generated by the plasma itself as an additional means of confinement, FRC-based designs may be able to use weaker external magnetic fields compared with other magnetic confinement approaches. While the plasma itself forms a torus shape, the reactor is linear. This idea has attracted entrepreneurs due to its potential for simpler engineering, more compact reactors and suitability for use with boron fuel, which is more readily available than tritium. However, plasmas in such devices have so far been found to require additional energy inputs for stabilisation compared with other magnetic confinement approaches.

In April 2025, TAE Technologies, a **US** start-up first founded in 1998, and the University of California, a US public university, reported FRC plasma generation at laboratory scale using a proprietary advanced particle accelerator technology. In June 2025, TAE Technologies raised USD 150 million to take its total equity raising to USD 1.3 billion. In December 2025, it announced a partnership with the **UK** Atomic Energy Authority, a public research institute, to jointly pursue commercialisation of the start-up's injector technology. This was followed soon after by the announcement of a merger with Trump Media & Technology Group to create the first publicly-traded fusion company in a deal valued at USD 6 billion. It plans to start building a 50 MW_e fusion power plant in 2026.

FRCs can also be applied to magneto-inertial confinement (see below). Two start-ups – Helion Energy and General Fusion – are pursuing such an approach.

Other magnetic confinement approaches, such as magnetic mirror reactors and levitated dipole reactors, are at earlier stages of development. In general, they are being pursued by scientists that are applying the latest digital and engineering tools to principles outlined in the early days of fusion energy research. In some cases, start-ups have raised tens of millions of dollars to build larger laboratory-scale reactors.

The state of innovation for other magnetic confinement approaches

Approach	Potential advantages and limitations	Recent progress
Axisymmetric magnetic mirror	Magnetic mirror approaches are linear and simpler than toroidal designs, and can, in theory, be operated in steady state, like stellarators. The “mirror” refers to the way that the magnetic field is reflected from each end of a tube. Magnetic mirror approaches were first proposed in the 1950s but have only recently become feasible with the availability of advanced controls. However, they tend to have relatively high energy losses and plasma densities.	In July 2024, researchers funded by the **US** government and Realta Fusion, a spin-off from a public university, reported plasma confinement, becoming the first device to integrate high-temperature superconducting magnets with multiple high-power plasma heating systems and advanced plasma controls in a laboratory test. In May 2025, Realta Fusion raised USD 36 million in equity, taking its total fundraising above USD 50 million. In June 2025, Novatron Fusion, a **Swedish** spin-off from a public university, inaugurated its first experimental prototype. In March 2025, the firm raised USD 11 million equity. Public finance has been involved in each of its funding rounds, and it has received an EU grant.
Centrifugal magnetic mirror	It is proposed that by rotating a mirror-shaped magnetised plasma to supersonic speeds it can maintain its heat while being stabilised and centrifugally confined. This could potentially eliminate the need for auxiliary heating systems and improve economics. There remain significant engineering challenges of high-voltage biasing and managing higher temperatures than achieved so far.	In May 2025, a **US** research team funded by the US government published initial results from a laboratory experiment using low-temperature superconducting magnets repurposed from medical equipment. Results showed fusion over a 1 second period with similar performance to other experimental tokamaks.

Approach	Potential advantages and limitations	Recent progress
Levitated dipole	By levitating a single ring-shaped superconducting magnet within a vacuum, plasma can be confined in a doughnut-shaped region around the magnet without the complex toroidal currents and external coils used in tokamaks. The concept remains at an experimental stage due to the challenges of combining levitation and extreme heat, as well as controlling the precise position of the levitating magnet.	In 2004, 5-10 second plasma discharges were achieved in an experiment at a **US** university funded by the US government, and a 40-minute levitation of a 560 kg magnet was demonstrated in 2007. In October 2024, OpenStar Technologies, a start-up from **New Zealand**, reported a 20-second plasma using high-temperature superconducting tape from Faraday Factory, a Japanese company.

Inertial confinement

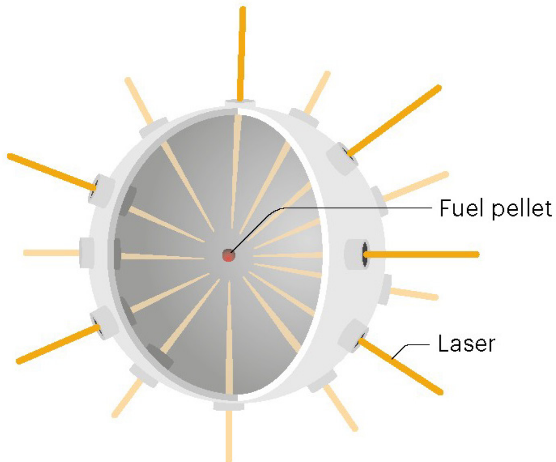
While inertial confinement was the first approach to achieve a momentary fuel ignition in 2022, its route to commercial fusion appears more challenging than for magnetic confinement. However, there are several ongoing avenues of research that may help overcome the engineering concerns associated with achieving more continuous operations, through higher repetition rate.

Inertial confinement terminology

- **Lamp-pumped solid-state lasers**. Light from an ionised gas (such as xenon) is used to excite electrons in a solid material (typically a compound of rare earth elements) so that they emit light in a specific frequency spectrum on demand. Lasers use multiple amplifiers and crystals to make the light energy more intense and the wavelengths shorter. A key challenge of laser research for fusion is the inefficiency of the charging process, including the energy used to operate the gas lamp.
- **Diode-pumped solid-state lasers**. Instead of a lamp, diodes produce the light that charges the laser. The light from diodes can be tuned more precisely and increase efficiency.
- **Direct drive.** Several lasers shine directly on the fuel pellet's outer surface to remove it, which produces a high-speed inward implosion that compresses and heats the fuel to fusion conditions.
- **Indirect Drive**. Lasers illuminate the inside of a cylinder, usually made of gold (known as a hohlraum), which converts laser light into soft X-rays that drive a more symmetric implosion of the fuel pellet inside the hohlraum.

- **Target**: The target is an assembly of one or more fuel pellets that are irradiated by a single laser "shot" to produce a fusion reaction. These pellets are sometimes inside a structure called a hohlraum.

The state of laser-based inertial confinement innovation



Most inertial confinement approaches use lasers as the means of heating, pressurising and imploding the fuel pellet. Since the 1970s, inertial confinement has been known to have lower potential efficiency than magnetic confinement, but research has continued, in part due to the technological synergies with detonation techniques for thermonuclear weapons. It was an inertial confinement device that first achieved ignition and Q>1 in 2022, with an indirect drive approach using 192 lasers at the **US** National Ignition Facility. Since then, ignition has been reached several times, and in 2025, an experiment at the same facility reached higher energy output and Q value. Also in 2025, 48 laser beams were used to produce a fusion reaction at Laser Mégajoule in **France**.

These achievements have not yet demonstrated sufficient reproducibility or efficiency to reach TRL 4 or justify investment in a MW-scale project. The National Ignition Facility experiment in 2025 used 0.6 kWh of energy input to generate 2.4 kWh of heat output, equivalent to Q=4.1. However, the calculation does not account for the more than 100 kWh of electricity used to charge the lasers, giving it an overall efficiency of 2% (not accounting for any upstream losses in the generation of input electricity). If the laser amplification process remains at less than 1% efficiency, and the efficiency of converting fusion heat to electricity at 40% or lower, it will be necessary to achieve Q values above 250 in order to deliver more electricity output than electricity input overall. Such Q values must be reached on demand. Longview Fusion Energy Systems, a US start-up, estimates that 20% laser efficiency will be needed for commercial operation, with a successful fusion shot and replacement of a fuel target 10-20 times per second. Today, one shot per day is possible.

Different lasers may be essential for the commercialisation of inertial confinement. Diode-pumped solid-state lasers could potentially raise efficiency towards commercial fusion needs. Recent advances have demonstrated higher repetition rates of diode-pumped solid-state lasers and more efficient cooling. Fully diode-pumped, high peak power laser systems are already in operation (e.g. L3 System at ELI, DIPOLE at CLF) showing major improvements compared to flashlamp pumped technology, but not yet at sufficient scale for inertial confinement. In August 2025, Inertia Enterprises, a US start-up with roots in US national laboratories, was founded to develop low-cost, mass-producible lasers and apply them in an indirect drive fusion reactor. Focused Energy, a **German-US** start-up spun out of publicly funded R&D, signed a USD 40 million agreement with Amplitude Laser, a French company, to develop two kilo-joule-class high-energy, high-repetition-rate diode-pumped laser systems.

New lasers for alternative fusion fuels

Laser innovation could open the possibility of using fuels that do not share the engineering challenges of deuterium-tritium (see Fuel cycle and new fuels section, below). In December 2024, HB11 Energy, an **Australian** spin-off from a public university, agreed to develop lasers for proton-boron fusion with ELI ERIC, a set of high-power laser research facilities funded and co-ordinated by the European Union. In 2024, Anubal Fusion, an **Indian** start-up, was founded to develop India's first petawatt lasers for proton-boron fusion in collaboration with the Tata Institute of Fundamental Research.

A key R&D focus is increasing the repetition rate of fusion "shots". As a commercial reactor may need to fire more than ten shots per second, processes for automated and repetitive fuel preparation, injection, laser charging, firing and removal of spent pellets are required. These processes would require millions of fuel targets to be supplied every month, but today, each target is expensive to produce and cannot be mass-manufactured.

Materials and reaction control are another avenue of innovation. Steel reactors would be weakened rapidly by neutron bombardment and become highly radioactive. In addition, debris from the reactor materials can interfere with subsequent reactions, significantly reducing efficiency. To overcome these concerns, researchers propose to execute the reaction inside a molten salt rather than a metallic structure, an approach that could allow reactor walls to last 30 years before replacement. To improve reaction control – fuel implosions have to date been asymmetrical and heat transfer has been sub-optimal – more precise laser targeting (in space and time), more spherical fuel pellets to an accuracy of thousandths of a millimetre, and greater harmony of the energy from all converging lasers are needed. One approach to smoothing the surface of a fuel target is to irradiate cryogenic hydrogen with a low-power infrared laser while monitoring it with a microscope-equipped camera.

Despite the historic milestones achieved with indirect drive, it is often considered less viable than direct drive in the long term, for reasons of efficiency and the complexity of fuel pellet manufacturing. There are several start-ups working on a direct drive approach:

- Longview Fusion Energy Systems, a **US** start-up founded in 2021, aims to build a 440 MW_e plant based on US National Ignition Facility tests. It has a partnership with a major engineering firm, but its level of funding so far limits its work to research projects.
- Focused Energy (see above) has an agreement with **German** utility RWE to explore a project for a 1 GW power plant. The company reports USD 200 million in equity (13%) and grants (87%) to build on work undertaken at the US National Ignition Facility.
- Blue Laser Fusion, a **US** start-up, is developing an advanced direct drive approach based on coherent beam-combining lasers and optical enhancement cavities. In November 2024, it announced a partnership with **Italian** public research agency RSE to construct a small-scale prototype reactor. This followed the company's successful test of its laser architecture and raising of over USD 60 million since 2023. Blue Laser Fusion has also won two US government R&D awards in 2025.
- In 2024 and 2025, First Light Fusion, a **UK** start-up, twice tested its fuel amplifier technology experimentally at a US national laboratory and increased the achievable pressure. Their target includes internal structures designed to amplify the laser energy or the energy deposition effect, resulting in greater compression efficiency or improved hotspot formation. It raised USD 108 million in equity between 2015 and 2022 and announced a new design in 2025.
- In 2025, GenF, a **French** joint venture, was created for direct drive approaches.

Other approaches to inertial confinement

Researchers and start-ups working on other approaches to inertial confinement are exploring modifications to materials, fuels or alternatives to lasers.

The state of innovation for other inertial confinement approaches

Approach (and TRL)	Potential advantages and limitations	Recent progress
Molten salt waterfall	If fusion explosions occur inside moving molten salt liquid instead of a steel-walled reactor, the reactor could have a longer lifetime. In addition, the molten salt would help transfer heat and, potentially, help produce tritium. The molten salt approach may limit the rate of fusion explosion and may entail corrosion challenges. The additional complexity of the system makes precise targeting of the fuel more difficult.	In June 2025, Xcimer Energy, a US start-up with roots in **US** national laboratory work, reported operation of a krypton fluoride excimer laser with the longest pulse length to date (3 microseconds). In 2024, the company raised USD 100 million to build the highest-energy laser facility in the world by 2030.
Non-thermal fusion	If boron fuel can be structured at the nano scale to fuse without the need for sustained high temperatures, then a compact reactor with no radioactive by-products could be possible. The charged particle outputs can be used to generate electricity directly without a steam cycle. Very precise lasers and laser controls at the femtosecond timescale are required, which are still under development.	In March 2025, Marvel Fusion, a **German** start-up, raised USD 53 million, taking its total fundraising in 3 years to over USD 120 million to build a prototype at a **US** university backed with US government funds. The company has received grant and equity funding from the European Union.
Pulsed-power indirect drive	The approach is similar to laser indirect drive, but electrical pulses are used instead of lasers. As well as a simpler design, this approach may allow higher repetition rates, which are needed for commercial power plants. This approach is much less mature than laser indirect drive. Very high electrical currents would be required and converting electrical energy to x-rays efficiently remains a challenge.	In 2020, a proposal for this approach was published by **US** national laboratory researchers. Early developmental work is underway at US national laboratories and a **UK** university.

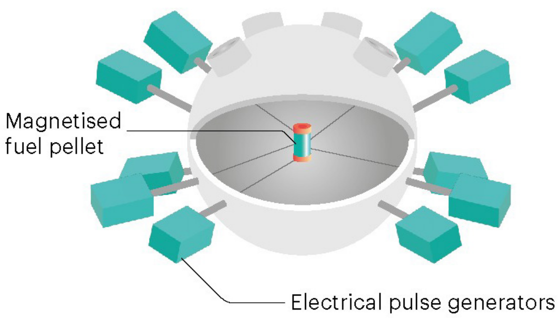
Magneto-inertial confinement

While less advanced than magnetic confinement, magneto-inertial confinement has been successfully used to produced plasmas and fuse small amounts of deuterium. Experiments to advance the two main approaches – magnetised liner and magnetised target – are being pursued in Canada and the United States, and planned in the United Kingdom.

Magneto-inertial confinement terminology

- **Magnetised liner**. The approach to magneto-inertial confinement used in the Z-Machine passes electricity along the sides of a linear fuel container to create a magnetic field around it and, after having heated the plasma, applies a massive pulsed-power current (10–25 MA) to forcefully implode the fuel liner inwards.
- **Magnetised target**. This approach first creates a magnetised plasma "target", then injects it into a different device that compresses it to fusion conditions, thereby reducing plasma losses. Different approaches to plasma creation are possible, including lasers and electrical currents. This approach implies lower densities but longer reaction times than in magnetised liner.
- **Impedance-matched Marx generator**. A technology for pulsed-magnetic power that is generally applied with magnetised liner approaches. Unlike lasers, it can go from charged capacitors to a pulse of energy in a single step, improving efficiency and simplicity. The theory was first tested in 2024.
- **Pulsed-magnetic plasmoid compression**. A third type of magneto-inertial confinement uses a linear fusion system where magnetic fields compress and accelerate a plasma target to fusion conditions, directly recovering electrical energy from the process. This would avoid a separate electricity generation step. Experiments have been made but evidence of plasma confinement and fusion are unavailable.

The state of magnetised liner innovation



Researchers have worked to combine magnetic and inertial confinement approaches since the 1960s, and the largest experimental facility to date is the Z-Machine at Sandia National Laboratories in the **United States**. This magnetised liner reactor is designed to produce plasmas that last for around 100 nanoseconds with temperatures of over two billion degrees Celsius. Fusion was first achieved there in 2014 and, in 2024, a doubling of experimental energy yield from a single shot was reported.

Z-Machine researchers plan to add tritium in the near future. This will introduce new challenges because it must be contained and prevented from contaminating any non-radioactive water in the vicinity, including the pools of water and oil that insulate components in magneto-inertial confinement systems. Adding just 1-3%

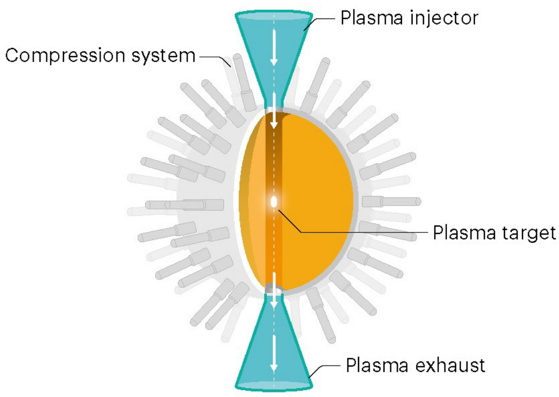
tritium will also require new approaches to ensure that metal walls do not become radioactive in areas where operators need to work.

Magneto-inertial confinement reactors are smaller and less costly than tokamaks, stellarators and inertial confinement reactors, making them more accessible to private companies. In October 2024, Pacific Fusion, a US start-up founded by former researchers at two US national laboratories, raised over USD 900 million to build a magnetised liner system capable of delivering 2 TW using an impedance-matched Marx generator, and electrodes to drive a massive current through the target. Their system is flexible and can use different compression strategies (shorter and high pressure or longer and low pressure). Their plan to reach positive net energy output by 2030 depends on successfully solving the engineering challenges associated with combining together 100-150 units of the largest one tested to date.

In 2023, MIFTI Fusion, a US start-up founded in 2008, reported the highest neutron yield of any private company in experimental conditions. MIFTI Fusion has received two US government grants and works on a publicly funded university reactor. In mid-2024, Fuse, a US start-up, reported successful testing of an impedance-matched Marx generator for magnetic liner fusion that achieved a 330 GW peak power. In the same year it raised USD 32 million in equity. The University of Rochester in the United States has also undertaken experiments in magnetised liner plasma formation.

While experimental results are encouraging, magnetised liner fusion still needs to achieve reproducible high Q values and fast replacement of the fuel target between shots, and to prevent cylinder particles mixing with fuel and plasma.

The state of magnetised target innovation



Plasma has been confined by magnetised target fusion at the **US** Air Force Research Laboratory's Directed Energy Lab and in **Canada** at LM26, a machine built by General Fusion, a Canadian start-up. In 2025, the start-up successfully compressed a magnetised plasma with lithium at the scale required for 75 MW_e. In August 2025, the company raised USD 22 million in equity, taking its total above USD 300 million, in pursuit of breakeven this decade and delivery of electricity to the grid in the 2030s. General Fusion's approach use a system of rotating piston and compressed gas driver to compress the preliminary heated plasma target and adds a liquid lithium "wall" to the reactor, which has the potential to reduce neutron damage and also be transformed into new fuel for the reaction. The company plans to go public with a valuation of USD 1 billion.

In 2013, US government researchers generated plasma using their one metre-long "field-reversed configuration" apparatus, but the timescales and temperatures fell short of the necessary levels for fusion. Higher magnetic fields and additional plasma injectors are proposed for the next feasibility tests. However, the current set-up requires weeks to prepare for each test, which are proceeding at less than one per year.

Helion Energy, a US start-up founded in 2009, is developing an approach similar to magnetised target fusion, and is building its seventh prototype. The reactor entered construction in July 2025, after the firm raised USD 425 million in January 2025, taking its total equity fundraising above USD 1 billion. Helion Energy aims to use the reactors to fulfil an agreement to supply electricity to a data centre from 2028 onwards. Its pulsed-magnetic plasmoid compression approach generates field-reversed configuration plasma at each end of a linear reactor and propels the plasmas into a collision in the centre, and then applies a final magnetic force to the merged plasma. Third-party verification of the viability of this approach is not yet available. The leading design is intended to use deuterium and helium-3 fuel, which would produce very fewer neutrons and little radioactive waste. While this fuel has been tested in limited quantities, commercial bulk production remains a challenge.

Like magnetised liner fusion, magnetised target fusion still needs to achieve reproducible high Q values and fast replacement of the fuel target between shots, and to prevent cylinder particles mixing with fuel and plasma. Both approaches also still face the challenge of minimising the loss of the material surrounding the fuel during each discharge. If the material must be replaced each time, then it is unlikely that electricity generation will be profitable, leading to research on the use of molten rather than solid liners.

Other confinement approaches

The following examples of other confinement approaches are less mature than the main three approaches. However, some are progressing rapidly through the earliest stages of development.

An alternative avenue of research is the combination of electrostatic forces with either inertial or magnetic confinement. As they do not rely on large magnet systems, their reactors can be made in relatively compact sizes. Of the two approaches, inertial electrostatic confinement is the more advanced due to its application to producing neutrons for uses in medicine and other fields, and the first commercial examples were sold in 2000. However, losses in existing examples would prevent them from ever achieving Q=1. The more complex magnetic electrostatic plasma confinement approach, if successfully developed, would be more suitable for large-scale power generation. To date, magnetic electrostatic plasma confinement reactors have been neither designed nor built.[30]

Another approach is the so-called "dense plasma focus" fusion, where the same electrical current is used to self-generate magnetic forces within the plasma that briefly accelerate and compress the plasma to a very small and dense mass to achieve fusion. Like inertial fusion, the approach uses "pulsing" so that the plasma is only confined for microseconds at a time. To date, this concept has been pursued primarily for producing neutrons for research purposes, but the simplicity of the equipment needed could lend itself to smaller-scale reactors for fusion energy in future.

A further (though not yet demonstrated) approach for fusion energy is muon-catalysed fusion. The principle is to use muons – a type of unstable subatomic particle 200 times heavier than an electron – to substitute electrons in hydrogen so that hydrogen atoms fuse together without high temperatures. However, while this phenomenon has been proposed since the 1950s, no-one has yet overcome several fundamental challenges:

- The energy required to obtain muons is currently greater than the energy produced from hydrogen atom fusion.
- Many muons will stick to alpha particles, which are the results of hydrogen fusion, and become inactive instead of catalysing more hydrogen fusion reactions.
- The decay time of muons (2.2 millionths of a second) requires a means of catalysing many fusion reactions in a very short timeframe.

The latest advance was the demonstration in 2024 by Acceleron Fusion, a **US** start-up working with US and **Swiss** national laboratories, of deuterium-tritium fusion on a lab-scale machine. This "diamond anvil cell" approach uses two polished diamond tips surrounded by a compressible fluid to compress sub-millimetre fuel to very high pressures and therefore high fuel densities that can reduce muon sticking losses. High-quality diamonds are expensive, and extreme pressures can damage or destroy them. Producing muons requires particle accelerators, which are large, expensive and energy intensive.

[30] Several challenges would first need to be overcome, including prevention and removal of impurities that would be trapped in the electrostatic charge with the plasma, reducing fuel density. A better understanding of the trajectories and velocities of electrons and alpha particles is also needed before a practical reactor can be made. There are additional remaining engineering considerations relating to how voltages above 100 kV can be sustained in the presence of hot plasma and radiation, and how changes in magnetic forces can be controlled without any loss in equipment precision.

Alternative approaches to plasma confinement innovation

Approach	Potential advantages and limitations	Recent progress
Spindle cusp with shielded grid	Opposing magnetic fields facing one another create a zone with no magnetic field along which plasma will pressurise and flow. This is the spindle cusp principle, and it is proposed for compact reactors, including for aviation. Plasma leakage outside the system is hard to control, and shielded grid techniques are designed to counter this. However, they are yet to be tested at larger than bench scales. Integrating magnetic and electrostatic confinement raises complexity. The required superconducting magnets have not been manufactured before at scale.	In November 2021, Horne Technologies, a **US** firm founded in 2008, reported fusion in its prototype device and began working on a larger reactor that is not yet operational. The company is developing novel rare earth barium-copper oxide superconductors.
Orbital ion trap (magneto-electrostatic)	By using electrostatic forces to propel ions in elliptical orbits (as used in mass spectrometry), high densities can be achieved with relatively weak magnetic forces and small equipment. Very high voltages are required to produce the necessary electrostatic forces. Integrating magnetic and electrostatic confinement raises complexity.	In July 2025, Avalanche Energy, a **US** start-up, received a government grant to build a test facility for the company's design of a modular 5 kWe reactor for onsite heat production, after demonstrating a capability to maintain 300 kV across a small distance.
Dense plasma focus	Fewer components are required than for magnetic confinement devices and can be constructed at a variety of scales. While it is more energy intensive per pulse than most other approaches, it can achieve higher densities and temperatures. It has not yet been possible to demonstrate Q values close to 1. Existing materials are unable to withstand the extreme reactor conditions during continuous use over long time periods.	In July 2025, LPP Fusion, a **US** start-up founded in 2003, reported a fusion energy output of 0.07 millionths of a kilowatt-hour using deuterium fuel. Its work has been funded by the US government, and it works with US and **Japanese** universities towards a modular 5 MW boron fuel reactor.
Efficient muon production	The potential of muon-catalysed fusion is limited by the energy requirements of muon production, which remain prohibitive today.	Several approaches to cost reduction are being pursued. NK LABS, a **US** engineering firm, seeks to optimise proton-target designs using machine-learning, among other techniques.

Technology landscape: integrated fusion energy plants

To date, most R&D efforts have been directed towards proving plasma confinement and fusion energy production, but many more elements will be required for a commercial power plant. Among the most significant remaining challenges in this category are the development of materials that can withstand the harsh conditions in a fusion reactor, a cost-effective fuel supply, and the integration of the power generation cycle, which has not yet been optimised for fusion power generation. No confinement system has yet been integrated with these ancillary components in a manner suitable for a commercial power plant, though some companies are pursuing early revenue by developing smaller commercial reactors that can serve niche markets without full integration of all aspects.

Fuel and power generation cycle terminology

- **First wall and divertor**. These elements make up the interior wall of the confinement system. The first wall must be durable in very harsh conditions and protect other components from intense heat and radiation. The divertor removes impurities and by-products to keep the plasma stable and has advanced material durability requirements beyond those of the first wall.
- **(Breeding) blanket**. See description in the box "Fusion energy terminology: a primer" (above).
- **Primary circuit**. A system that circulates a working fluid through or around the reactor to absorb heat, cool the reactor and transfer heat away from the reactor. This working fluid, which in nuclear fission reactors is typically water, can either directly power a turbine or other electricity generator or, more commonly, transfer its heat to a secondary circuit.
- **Secondary circuit**. A system that takes heat from the primary circuit, typically at a lower temperature and pressure, without its working fluid coming into contact with the working fluid of the primary circuit. The secondary circuit can have a different working fluid from the primary circuit.

Materials for confinement system durability

Materials that can withstand very high temperatures, pressures and neutron bombardment are vital to the achievement of fusion energy. Unless reactor materials can last for decades without excessive degradation or costly replacements, competitively priced fusion power will likely remain out of reach. This is especially true for the deuterium-tritium-fuel-based approaches, in which some components spend longer time in contact with plasma at high temperatures and radioactivity levels. Alternative fuels that involve lower temperatures or radiation would make these issues easier to resolve, but they tend to require achieving even more challenging initial conditions to work.

Many teams are working on solutions to the challenges they encounter, but it is hard to stress-test designs and interactions of materials without operating at scale. The pilot plants and dedicated facilities that are being built and operated this decade (including the publicly funded USD 760 million "International Fusion Materials Irradiation Facility – DEMO-Oriented Neutron Source" facility that started construction in **Spain** in 2023) will generate important information that can inform

R&D and be transferred collaboratively to the next generations of designs. For example, a primary goal of the experiment that set the record for confinement duration in the WEST experimental device was to test the resistance of tungsten components in contact with plasma.

The material innovation needs for a reactor vary by type of component.

- **First wall and divertor**. Tungsten, beryllium- and graphite-based materials are currently used in many experimental facilities, but they suffer degradation under reactor conditions that is too fast for commercial operation. Graphite, in particular retains a significant amount of tritium and produces dust that reduces efficiency. Advanced tungsten alloys and composites may address this issue. While research into new tungsten alloys or composites is ongoing, a promising option may be a flowing layer of liquid metals – typically lithium, tin, or their alloys. A liquid metal surface is continuously replenished, can withstand extreme heat and transfers heat efficiently to the blanket. Controlling magnetohydrodynamic flow in strong magnetic fields and injection of the lithium remain research challenges with such an approach. A more recently proposed method is to vaporise liquid lithium at the base of a tokamak to absorb excess heat and spreading it over a larger area without cooling the plasma.
- **Blanket**. The blanket is usually made of ferritic or martensitic steels. To make the blanket more durable, silicon carbide composites are under development that can withstand temperatures above 1 500°C without corrosion while retaining mechanical strength and thermal conductivity. For commercial applications they need to be manufactured with higher purity, lower brittleness, in larger sizes and with more complex designs than is possible with today's chemistry and jointing. This is the subject of a major pillar of work within the ITER consortium and in UK research. If researchers in projects co-ordinated by EUROFusion, a public European programme, the US Government and General Atomics, a US company, can deliver these requirements, the results could also be valuable for nuclear fission fuel cladding and power transmission. To enable tritium production within the blanket, the use of solid ceramics, liquid metals or molten salts are being explored, with the latter two options potentially also acting as a coolant.

Fuel cycle and new fuels

Nearly all fusion energy systems work with the same basic fuel concept, which is the combination of two hydrogen atoms to create a helium atom and release a highly energetic neutron. However, this process does not work with the most common hydrogen atoms; it requires atoms that have neutrons in their nuclei, in addition to one proton. Most existing experimental work fuses two deuterium atoms because tritium is more expensive and requires more careful handling. However, it is generally accepted that commercial nuclear fusion power generation will fuse one deuterium nucleus with one tritium nucleus.

As with nuclear fission, fuels – such as deuterium and tritium – must be continually supplied to a fusion reactor. Compared with nuclear fission, less energy output (around one-tenth) is created from each atomic reaction and much more energy input is usually required to create the necessary conditions for the fuel to react. However, per unit of mass, a deuterium-tritium fusion reaction can deliver three to four times more energy than uranium fission. Fusion energy also has the significant advantages of using a fuel that can be produced without scarce raw materials and not produce radioactive spent fuel waste.

While techniques for producing deuterium and tritium are known – deuterium is supplied via water electrolysis, for example – innovation will be needed to improve the costs and availability of tritium for fusion. A reactor would need a steady supply of an isotope of lithium (lithium-6) that represents less than 10% of natural lithium supplies. For a 1 GW_e fusion reactor, an annual supply of less than 5 tonnes of naturally occurring lithium may be adequate, and this would need to be combined with a metal such as titanium and silicon or fluoride-beryllium salts to make a breeding blanket. For comparison, global lithium demand for batteries in 2024 was over 100 000 tonnes. In addition, the annual amount of water required to supply the deuterium fuel would be roughly equivalent to the volume of several Olympic-sized swimming pools, much less than the water for cooling and other utilities that the plant would require overall. However, the production of lithium-6 and effective breeding blanket designs require further innovation to become commercially viable.

Avenues of innovation for supplying tritium fuel

Approach	Potential advantages and limitations	Recent progress
Laser production of lithium-6	By precisely tuning lasers to a specific isotope's spectrum colour signature, atoms can be selectively photoionised and then electrically separated. This could potentially be higher yielding and more energy efficient. The approach has yet to be scaled above laboratory operations.	In 2023, ASP Isotopes, a **US** manufacturer of medical isotopes spun-out Quantum leap energy to work on the production of Lithium-6 among other products. In April 2025, Hexium, a **US** start-up with roots in public laboratory research, raised USD 9.5 million in equity to develop a laser-driven approach.
Electro chemical capture of lithium-6	Vanadium oxide can be used to separate lithium-6 from lithium-7 in water when used in an electrochemical cell. This overcomes the need for toxic mercury in lithium-6 production. The process has so far been tested only on clean water sources and requires looping the solution through the cell multiple times.	In April 2025, researchers from the **United States**, **Qatar**, **Canada** and **Switzerland** reported promising laboratory results.
Breeding blanket: solid ceramics	Arranging lithium ceramate or lithium orthosilicate pebbles as the solid breeder material, and beryllium pebbles as a neutron multiplier around the tokamak	A research programme within the ITER consortium is working on three different solid ceramic

Approach	Potential advantages and limitations	Recent progress
	plasma chamber potentially offers safety, simplicity and stability benefits. However, a separate coolant medium is required.	systems in **China**, **Japan**, **Korea** and some **European** countries.
Breeding blanket: liquid metal	As a means of producing tritium from lithium in tokamaks, a liquid mixture of lead and lithium could have a higher tritium production efficiency than solid or water-cooled methods, and also provide higher levels of radiation shielding and coolant properties. The mixture of lead and lithium could be highly corrosive to structural materials, requiring advanced coatings. As with other approaches to tritium breeding, efficiently extracting tritium is technically demanding.	A research programme within the ITER consortium is working on a water-cooled design in Europe. In 2022, Kyoto Fusioneering, a **Japanese** spin-off from a state university, published a design concept. Since 2024, the company has been building a test rig and has a partnership with **Canadian** Nuclear Laboratories, a government entity. It began commissioning in mid-2025.
Breeding Blanket: molten salt	Molten salts, including lithium fluoride and beryllium fluoride mixtures, have high chemical stability and low vapour pressure, which can allow reactor designs to be simpler than if liquid metal is used. Molten salts can be corrosive to structural materials at elevated temperatures, requiring advanced reactor materials or protective coatings.	In 2025, the University of Edinburgh, in the **UK**, was awarded a UK government grant for work in this area. In 2021, MIT, a **US** university, began a research programme on molten salt breeding blankets.

Some fusion energy concepts do not propose using deuterium-tritium fuel. With other fuels the fusion reaction is more difficult to achieve but, if successful, they could eliminate some of the challenges associated with fuel supply, extreme temperatures, radioactivity and power generation cycles.

- **Lithium and deuterium**. A cited benefit of this type of fusion is that the energy-carrying particles from the fusion reaction are charged alpha particles and protons that may be converted directly to electricity without a secondary cooling loop and turbine. It would also not require the use of a breeding blanket to transform the lithium isotope into tritium. However, it requires much more extreme conditions to cause fusion.
- **Proton-Boron.** Boron – used in its most abundant form – would be a readily available, non-toxic and non-radioactive fuel for an inertial confinement plasma. Boron atoms would first split to produce alpha particles and then other boron atoms would fuse with them to form non-radioactive nitrogen or boron. As for lithium and deuterium, it may be possible to convert charged particles directly to electricity. However, boron plasma formation requires much more energy and for a longer time than for deuterium and tritium, thus presenting a greater engineering challenge. In 2023, **Japan**'s Institute for Fusion Science and TAE Technologies, a **US** start-up, reported the first fusion reaction using this fuel via magnetic confinement, following several examples since 2000 using inertial confinement. A further option – using a rotating electric and magnetic field – is being developed at "tabletop" scale by Alpha Ring, a US start-up with roots in a public university.

- **Deuterium and Helium-3**. Unlike proton-boron, this reaction can be achieved at scale with current technical capabilities. It produces few neutrons that damage materials and create radioactive waste. The charged alpha particles that are produced could potentially be converted directly to electricity. But this approach has typically faced significant plasma instability challenges. Helium-3 is not naturally occurring and must be bred from deuterium reactions. Higher temperatures than the ones in D-T fuel operations are needed. Helion Energy, a **US** start-up developing a magneto-inertial approach, is using this fuel.
- **Proton-Lithium**. Lithium's atomic properties make it more amenable than boron to becoming a plasma with quantum properties, which may lower the energy required for ignition. This fuel combination would also produce no damaging neutrons. While theoretically interesting, this approach still faces significant technical and scientific challenges. In 2022, Electric Fusion Systems, a **US** start-up, filed a patent for an apparatus that could potentially be used for this approach.

A separate challenge faces inertial confinement approaches and some magneto-inertial confinement approaches. Fuel targets must be mass-produced for commercial applications on the order of several millions per month for a single reactor. For this, cost-effective manufacturing process will be needed.

Power generation cycles

Fusion reactors are expected to have much higher temperatures than nuclear fission reactors and, while water is a leading candidate for secondary circuits, different working fluids for primary circuits are proposed, including molten salts, lithium or helium. In systems that would generate tritium within the reactor, the working fluid may also need to participate in tritium recovery, making tritium solubility a factor to consider.

Technology innovation will be important for adapting power generation cycles to new working fluids or more extreme conditions. Given the current state of development of fusion power generation cycles, if the first projects that generate electricity are commissioned as promised in the next decade, they are unlikely to be optimised for high-efficiency operation. While this may not pose a problem for demonstration of feasibility, further work will be required before gigawatts of installations can be considered. Recent research has tested the corrosivity of candidate molten salts towards reactor materials. Supercritical carbon dioxide secondary circuits have not yet been designed or tested for fusion energy, but initial calculations indicate it could be an efficient system for a large-scale tokamak. The Helium Cooled Pebble Bed concept is one of two approaches considered for heat and tritium transfer in a future larger tokamak after the current ITER project, though the use of helium as a working fluid for the primary circuit in a power plant is untested and could have high pumping requirements due to its low density.

Efforts are also underway to develop reactors that do not need a separate power generation cycle. These include work on magneto-inertial confinement designs in which the plasma interacts with the magnetic field to stimulate an electric current directly, something that is being developed in a pilot project under construction in the **United States**. Another avenue at a more theoretical stage of development is non-thermal inertial proton-boron fusion, in which the charged particle outputs could directly create electric current (see discussion of inertial confinement, above).

Compact designs and miniaturisation

The project teams designing fusion energy plants for the 2030s are paying more attention to reactor size than their predecessors working with experimental reactors. To demonstrate the potential for cost-competitiveness, new engineering approaches are being explored to ensure that plants are as compact as possible. Per MW, tokamaks like ITER and Commonwealth Fusion Systems' SPARC project will have sizes that around four times smaller than the Joint European Torus, which was decommissioned in 2023. Reducing material needs is an important element of cost reduction. For magnetic confinement, this includes keeping the cooling systems as small as possible by using high-temperature superconductors. For inertial confinement, more efficient, higher power (over 10 MW) and more compact laser pumping technology will be needed, given that the 192 lasers at the National Ignition Facility occupy a 16 000 m^2 building and the layout has limited potential for reconfiguration.

While comparisons with nuclear fission reactor sizes are inevitable, they are misplaced. The land area for both types of power plants must take into account the radioactivity exclusion zone, which is far larger than the reactor for a nuclear fission plant. For fusion energy, the exclusion zone can be much smaller, reducing the total land required. In terms of visual impact, the cooling system of a nuclear fission plant typically determines the height of the structures wherever cooling towers are needed. The same will be true for fusion energy.

At the other end of the scale, there are compact reactor proposals for very small-scale fusion energy. These include proton-lithium quantum plasma state fusion (5 kW_e modules), orbital ion trap electrostatic confinement (0.1 to 1 MW_e), spindle cusp electrostatic confinement with shielded grid (0.1 to 10 MW_e), dense plasma focus electrical discharge confinement (5 MW_e), dynamic stellarator (20 MW_e), sheared-flow-stabilised Z-pinch magnetic confinement (50 MW_e modules), axisymmetric magnetic mirror confinement (minimum 50 MW_e size) and helical stellarators (minimum 50 MW_e size).

Alternative scale-up pathways

Moving from the laboratory-scale testing of a novel component for a future commercial fusion plant to integrating it into a multi-megawatt pilot plant is a big step that can cost hundreds of millions of dollars. Through co-operation between governments, as in the ITER project, large sums of money can be accessed for such plants, but the bureaucracy and budgets involved typically lead to long lead times and a very small number of such efforts worldwide. Some governments – such as China, Germany and the United States – have internal resources sufficient to fund pilot plants for large-scale designs. However, in recent years, with many new ideas being spun off from public R&D programmes into start-ups, it has become clear that there is insufficient public and private capital for them all to follow a traditional path from laboratory to pilot plat to large-scale demonstration.

A venture-backed start-up working on fusion typically needs to raise equity for a 5-10-year project that demonstrates technical milestones before returning to investors to request money for further scale-up. The need to demonstrate results quickly, with limited funds, is one reason why many firms are exploring how to sell the core component or materials technology to other fusion developers or non-fusion markets to start generating early revenue, or how to make modular and decentralised reactors that do not need to be scaled up to hundreds of MW at all. Commonwealth Fusion Systems, a tokamak developer, has agreed to sell its magnets to Type One Energy, which is developing a stellarator.

An example of non-fusion energy opportunities to generate early revenue includes the supply of superconducting magnets to other fusion experiments, and potentially for superconducting components for electricity distribution. Another example is the use of a small dense plasma focus machine to generate x-rays for inspection of infrastructure wear, including for bridges. In March 2025, First Light Fusion, a **UK**-based start-up, refocused its near-term plans on using its amplifier technology with national space agencies to test how materials sent into space react under conditions that otherwise cannot be replicated. Other companies use their fusion technology to produce medical isotopes. SHINE Technologies, a **US** company with facilities in the United States and the **Netherlands**, has published a four-step approach to scale-up of its technology, in which recycling nuclear waste could be an application in between medical isotopes and fusion power plants. In 2025 in **China**, the government reportedly approved construction of a USD 2.8 billion nuclear fission power plant that will use a fusion device to generate neutrons to trigger the fission reaction and potentially breed more fission fuel.

Pursuing other commercial opportunities is not appropriate for all fusion energy teams, but for certain developers it will provide valuable pressure to refine and stress-test designs under cost-sensitive conditions.

Knowledge gaps to be filled

The summaries in this chapter show that fusion energy still faces a wide variety of innovation challenges. While it is unable to capture all the different experiments and efforts that have cost many billions of dollars since the 1950s, the chapter presents the diverse range of public and private advances in recent years. These projects and research teams will collectively need to overcome a range of significant barriers before the first grid-connected fusion energy plant is demonstrated. This will require many more billions of dollars to be spent testing different elements that could in future comprise a working system, from fuel production to construction, operation and safe handling. Government funding programmes continue to allocate resources to arising challenges. Given that there remain decades of development ahead, and new combinations of ideas will arise, the various teams focusing on different parts of the overall problem are not in direct competition with one another, as long as the learnings are shared between them. However, as long as funding is limited, they are in competition for financing for their next projects.

It is important for governments and other funders to ensure that the available funds are spread appropriately among key groups of outstanding knowledge gaps.

- **Demonstrate Q=10 with high reproducibility**. This threshold is generally considered to be the point at which a reactor performs efficiently enough to be integrated into an overall system that produces more electricity output than its inputs. Whether this can be achieved will not be known until it is demonstrated, and today's leading approaches may or may not ultimately be the first to succeed. Most experimental projects today are working on deuterium-deuterium reactions before moving to the more complex deuterium-tritium operations that are expected to get to Q-10. A reproducible reaction is one that can be turned on and ramped up and down reliably over periods of many days.
- **Breed and capture tritium fuel at high temperatures without affecting the fusion reaction**. For as long as the deuterium-tritium reaction remains the leading option among developers, a dependable mode of producing tritium onsite from lithium, such as within the reactor itself, is imperative. The various concepts for breeding blankets, mostly designed for use in tokamaks, are still at a relatively early stage in terms of their materials, coolants and tritium extraction methods.
- **Develop materials designs that can withstand neutron bombardment and extreme conditions years before replacement.** For commercial power plants with high capital costs, multi-decade operations without major refurbishments are fundamental to the economics. Research is ongoing around the effects of neutron irradiation on materials for reactors, fuel targets, working fluids and other components. Much of this work is inconclusive so far and a great deal of important information will be learned from the next wave of pilot plants.

- **Remove heat from the reaction chamber so it can drive a turbine without interfering with the fusion reaction**. The first fusion energy plant that generates electricity may demonstrate the concept by applying power generation cycles developed for nuclear fission to a fusion reactor by allowing the heat output to cool first. However, efficient, commercial operation will require a more tailored approach that accounts for the higher temperatures and harsher conditions in a fusion reactor. There is ongoing theoretical work into options for a primary heat transfer circuit using liquid metals, molten salts or helium, and for secondary circuits using supercritical carbon dioxide. The next step is to test these possibilities in practical experiments.
- **Make reactors more compact and reproduceable with acceptable construction times**. If scaled up with current designs, tokamaks and stellarators at scales of hundreds of MW_e will have material costs that cannot deliver long-term cost-competitiveness. In addition, the first generations of demonstration projects are not all being designed with reproduceable engineering and construction as a primary concern. Once fusion heat production at an acceptable scale for commercial operations is demonstrated in each category of reactor approach that reaches that stage, attention will need to turn to industrialisation of manufacture and installation. Encouragingly, some developers are making an early start, pressed in part by the venture-backed funding model. The manufacturable superconducting coil approach of Commonwealth Fusion Systems is an example.

Priorities for reaching the next innovation stages

With so many avenues of research and approaches to commercialising fusion energy, pinpointing just a few top priorities for governments and investors is difficult. For some technologies – such as tokamaks, stellarators, laser indirect drive inertial confinement and leading magneto-inertial confinement approaches – there are clear and essential next steps: demonstrate engineering breakeven, finalise engineering design and then build pilot reactors at scales of MW_e. Such plants will cost hundreds of millions, or even billions, of dollars to construct and operate, but they are key to solving remaining scientific challenges outside the laboratory and proving feasibility of plasma control for many minutes at a time. There is also space for other approaches and there are likely to be benefits to diversifying the global portfolio of confinement approaches instead of betting on one or two concepts. For other approaches, smaller-scale projects are needed wherever experts agree that the concepts have long-term potential to accumulate gigawatts of installed capacity.

A striking feature of existing projects and scientific publication on fusion energy, compared with other energy technologies, is the international nature of co-operation and the ubiquity of publicly funded research. This indicates that fusion energy is still at a stage where rapid scientific problem-solving is more important than protecting intellectual property for near-term commercial exploitation. However, the level of interest in fusion energy today, and the language of international competition that has begun to be evoked in government announcements, presents a potential risk to international co-operation. One priority for enabling development to proceed as fast as practicable is to reinforce the institutions that facilitate bilateral and multilateral collaboration and burden-sharing. No country alone can take on all the pilot and demonstration projects that are proposed, and all these projects could hold insights for their peers in partner countries, for example in relation to materials performance. Institutions such as the IAEA (which in 2024 launched the inaugural Ministerial Meeting of its World Fusion Energy Groug [WFEG]), ITER, the IEA Technology Collaboration Programmes (TCPs) and EUROFusion are already in place and can play key roles in appropriately sharing knowledge from projects.

The IEA Fusion Power Coordinating Committee and TCPs

Since its founding in 1975, the IEA Fusion Power Coordinating Committee (FPCC), has co-ordinated a variety of activities on fusion. Today, 19 IEA Member countries, the European Commission, the Nuclear Energy Agency (NEA) and IAEA are members of the FPCC. For five decades, it has overseen the IEA TCPs that work on different aspects of fusion energy.

Four TCPs cover magnetic confinement approaches:

- Tokamak Programmes, which contributes to design work, such as for ITER.
- Stellarators and Heliotrons, which works on physics R&D for these concepts.
- Spherical Tori, which supports co-operation on spherical torus R&D.
- Reversed Field Pinches, which supports R&D co-operation on this concept.

Four TCPs cover the development of integrated power plants:

- Environmental, Safety and Economic Aspects of Fusion Power, which communicates progress to governments and the public.
- Fusion Materials, which co-ordinates R&D on advanced reactor materials.
- Nuclear Technology of Fusion Reactors, which supports work on radiation protection within fusion energy plants.
- Plasma Wall Interaction, which researches materials in contact with plasma.

Several of the IEA fusion TCPs have played important roles in advancing the physics and engineering basis for the ITER project, as well as ensuring a high degree of international knowledge exchange via conferences and publications.

Areas that are natural candidates for international co-operation, and can inform advances across different technological areas and scale, include:

- Materials development and testing
- Tritium breeding and alternative fuels
- Novel coolants
- Waste management
- Regulatory approaches that protect citizens while enabling faster permitting for lower radioactivity levels compared with nuclear fission.

The high levels of cross-fertilisation of research between teams and countries over the past five decades of research in this area reaffirms that the fastest path to gigawatt-scale fusion energy is an international one. This is likely to be true even if smaller firms with a domestic outlook lead the development of certain reactor designs. While there remains much uncertainty, such a pathway could foreseeably proceed to MW-scale pilot reactors in the 2030s, followed by scale-up of the most promising of these to commercial-scale and more optimised plants in the 2040s. Some of these plants could generate electricity and supply users, but power generation may not be part of the initial scale-up trajectory for all approaches. If these plants operate continuously, effectively and safely for long periods, it is feasible that the best designs, which will likely combine elements of today's various approaches in new ways, could attract debt capital to start construction of commercial grid-connected installations at gigawatt scale.

Annex A. Data tables

Energy R&D spending in countries participating in IEA RD&D budget data-sharing

Country	Energy R&D spending Million USD (2024, MER)					
	2021	2022	2023	2024	2025	% of GDP in 2024
Australia	277	413	293	125	71	0.007%
Austria	280	256	347	434	-	0.083%
Belgium	221	404	528	549	-	0.083%
Brazil	856	779	1 056	0	-	-
Canada	1 163	1 133	1 401	1 561	1 229	0.070%
Chile	2	3	9	0	-	
Czechia	160	123	98	78	75	0.023%
Denmark	200	126	123	146	-	0.034%
Estonia	2	10	2	1	-	0.003%
Finland	170	186	211	0	-	-
France	2 227	2 383	2 565	2 658	-	0.084%
Germany	1 715	1 768	1 630	0	-	-
Hungary	89	9	7	7	-	0.003%
Ireland	30	38	45	52	-	0.009%
Italy	688	631	0	0	-	0.067%
Japan	2 215	2 164	2 241	2 698	-	0.033%

Country	Energy R&D spending Million USD (2024, MER) 2021	2022	2023	2024	2025	% of GDP in 2024
Korea	698	695	723	624	-	-
Latvia	49	45	52	0	-	-
Lithuania	14	16	20	7	106	0.009%
Mexico	25	6	2	30	-	0.002%
Netherlands	543	353	173	412	-	0.034%
New Zealand	15	16	6	0	487	-
Norway	497	383	477	684	-	0.141%
Poland	147	239	183	45	-	0.005%
Portugal	94	96	98	0	3	-
Türkiye	46	27	29	37	-	0.003%
Slovak Republic	11	10	13	4	-	0.003%
Spain	824	1 536	2 155	0	247	-
Sweden	303	286	281	283	-	0.047%
Switzerland	403	372	435	429	-	0.046%
United Kingdom	1 547	1 489	1 752	2 085	17	0.057%
European Union funding	5 443	7 561	9 197	5 294	-	-
United States*	-	-	-	-	-	-

* The IEA is unable to provide official data on US federal energy technology RD&D spending from 2016 onwards due to a lack of US government submissions.

Notes: MER = market exchange rates. Hyphens indicate an absence of reported data. See the metadata for more information on the programmes included and national approaches to including budget or spending data.

Source: IEA Energy Technology RD&D Budgets database, accessed February 2026.

Top three areas of energy R&D by spending for countries participating in IEA RD&D budget data-sharing

Country	1st largest	2nd largest	3rd largest
Australia	Renewable energy sources	Hydrogen and fuel cells	Other power and storage technologies
Austria	Energy efficiency	Renewable energy sources	Hydrogen and fuel cells
Belgium	Nuclear	Energy efficiency	Hydrogen and fuel cells
Brazil	Fossil Fuels	Other cross-cutting techs/research	Renewable energy sources
Canada	Energy efficiency	Nuclear	Fossil Fuels
Chile	Hydrogen and fuel cells	Renewable energy sources	Energy efficiency
Czechia	Nuclear	Energy efficiency	Other power and storage technologies
Denmark	Renewable energy sources	Energy efficiency	Fossil fuels
Estonia	Other power and storage technologies	Renewable energy sources	Other cross-cutting techs/research
Finland	Energy efficiency	Nuclear	Other power and storage technologies
France	Nuclear	Energy efficiency	Hydrogen and fuel cells
Germany	Hydrogen and fuel cells	Renewable energy sources	Energy efficiency
Hungary	Other power and storage technologies	Nuclear	Renewable energy sources
Ireland	Renewable energy sources	Energy efficiency	Other power and storage technologies
Italy	Nuclear	Energy Efficiency	Renewable energy sources
Japan	Nuclear	Energy efficiency	Fossil fuels
Korea	Energy efficiency	Nuclear	Hydrogen and fuel cells
Latvia	Other power and storage technologies	Other cross-cutting techs/research	-

Country	1st largest	2nd largest	3rd largest
Lithuania	Renewable energy sources	Other power and storage technologies	Nuclear
Mexico	Fossil fuels	Other power and storage technologies	Renewable energy sources
Netherlands	Energy efficiency	Renewable energy sources	Fossil fuels
New Zealand	Renewable energy sources	Energy efficiency	Other power and storage technologies
Norway	Energy Efficiency	Fossil Fuels	Hydrogen and fuel cells
Poland	Renewable energy sources	Hydrogen and fuel cells	Other cross-cutting techs/research
Portugal	Energy efficiency	Renewable energy sources	Other cross-cutting techs/research
Slovak Republic	Energy efficiency	Other power and storage technologies	Nuclear
Spain	Energy Efficiency	Hydrogen and fuel cells	Renewable energy sources
Sweden	Energy efficiency	Hydrogen and fuel cells	Renewable energy sources
Switzerland	Renewable energy sources	Energy efficiency	Other power and storage technologies
Türkiye	Renewable energy sources	Other power and storage technologies	Energy efficiency
United Kingdom	Nuclear	Energy efficiency	Renewable energy sources
European Union funding	Nuclear	Other power and storage technologies	Renewable energy sources

* Indicates provisional data estimated by the IEA in the absence of nationally submitted data.

Notes: Order reflects size of reported budget to each technology area. Hyphens indicate an absence of reported data. Categories are drawn from the 2011 edition of the IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics.

Source: IEA Energy Technology RD&D Budgets database, accessed February 2026.

Energy venture capital fundraising by location of start-up headquarters

Country	Energy R&D spending Million USD (2024, MER)				Number of start-ups funded, 2025	Top area 2025
	2022	2023	2024	2025		
Australia	227	232	335	358	18	Electricity grids
Austria	22	37	119	59	5	Electricity grids
Belgium	47	34	267	5	3	CCUS
Canada	1 781	1 224	616	781	36	Nuclear
Chile	-	70	6	-	-	-
Czechia	18	22	7	-	-	-
Denmark	99	102	175	167	10	Hydrogen and fuel cells
Estonia	46	92	82	42	10	Hydrogen and fuel cells
Finland	23	246	57	310	7	End-use: transport
France	1 919	2 382	1 303	1 453	29	End-use: transport
Germany	1 936	1 091	1 233	1 448	50	End-use: transport
Hungary	-	-	-	-	-	-
Ireland	333	410	332	48	4	End-use: transport
Italy	33	359	52	44	14	Electricity grids
Japan	77	118	381	346	16	End-use: transport
Korea	121	107	121	66	7	End-use: transport
Latvia	67	32	2	63	3	Renewable energy
Lithuania	8	106	-	-	-	-

Country	Energy R&D spending Million USD (2024, MER) 2022	2023	2024	2025	Number of start-ups funded, 2025	Top area 2025
Mexico	33	1	76	282	3	End-use: transport
Netherlands	437	349	504	245	27	Electricity grids
New Zealand	9	35	25	10	1	End-use: transport
Norway	368	246	83	95	7	Hydrogen and fuel cells
Poland	75	1	9	5	1	End-use: transport
Portugal	211	68	15	2	1	Electricity grids
Türkiye	6	62	5	9	3	Energy efficiency
Slovak Republic	9	18	119	43	1	Renewable energy
Spain	304	99	123	192	15	Hydrogen and fuel cells
Sweden	1 052	2 588	955	491	22	Energy efficiency in buildings and industry
Switzerland	906	135	249	281	15	CCUS
United Kingdom	2 442	1 303	2 297	2 003	60	Electricity grids
United States	20 040	10 383	12 788	13 921	229	Nuclear
China	8 202	9 205	5 942	1 890	41	End-use: transport
India	1 406	2 196	1 790	867	44	End-use: transport
Brazil	26	80	42	44	1	End-use: transport

Notes: MER = market exchange rates. CCUS = carbon capture, utilisation and storage, including engineered carbon dioxide removal technologies. Data in the table covers more than 95% of the global total. Categories broadly follow the 2025 edition of the IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics, though energy storage is separated from electricity grids and transport in the venture capital dataset.

Sources: IEA analysis based on data from Cleantech Group (2025) and Crunchbase (2025).

Annex B. Methodological notes

Innovation spending data

Three types of spending data are tracked in the report: public R&D, corporate R&D and venture capital investment.

Where spending is allocated to technology areas, the IEA energy technology classification is used as the guiding principle. However, as this classification is in the process of being updated from the 2011 edition to the 2025 edition, some small inconsistencies exist. These are covered in the descriptions of each spending type, below. Where aggregate values are given for low-emissions technologies, this encompasses energy efficiency; renewable energy; nuclear; carbon capture, utilisation and storage (CCUS); electricity grids; electric mobility; industrial electrification; energy storage; hydrogen and hydrogen-based fuels.[31]

Public R&D

Public energy R&D data come mainly from the IEA Energy Technology RD&D Budgets database, a compilation of submissions each year from IEA Member governments and Brazil. As of the end of 2025, data are available for most countries for 2024 and several national estimations for 2025 have been received. Metadata for the dataset, including the treatment of state-owned enterprises by different governments, is available online. In some cases, publicly available information is used to extrapolate or interpolate the trend for IEA Member countries when producing regional aggregate estimates. It mostly covers grant funding as data on the allocation and value of concessional debt and tax breaks for energy innovation are scarce.

Up to 2024, countries shared R&D spending with the IEA on the basis of the 2011 edition of the IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics, and this is the classification used in the report. The IEA secretariat is in the process of mapping historical spending to the classification in the 2025 edition. The main differences are small. At a high level of aggregation, they correspond mainly to the way that CCUS and hydrogen technologies are allocated. This is described in the documentation of the 2025 edition.

Annual estimates are produced for non-IEA Member countries based on publicly available sources. Notable sources include: data submissions to the Mission

[31] Cross-cutting and unallocated values are also assigned to low-emissions in the absence of precise information.

Innovation (MI) Secretariat; China Yearbook on Science and Technology Activities of Industrial Enterprises; China Statistical Yearbook on Science and Technology; China state-owned enterprise annual reports; reports of the ITER project; India Research budgets of energy-related ministries; South Africa Budget reports of the Department of Energy and SANEDI.

Corporate R&D

Data on corporate R&D are taken from the annual financial statements of companies, mostly those that are listed on stock exchanges around the world. Corporate financial reports of over 3 000 companies active in energy sector industry classifications are included in the sample. These classifications include: fossil fuel extraction, transport, conversion and services; electricity generation, including production, equipment manufacture and services; electricity, gas and district heating utilities; electricity and gas networks and smart grids; mobility; industry and electronics; LEDs; insulation; electricity storage, hydrogen and fuel cells; non-electricity renewable energy, including production and equipment manufacturing.

Disclosed R&D budgets are not itemised in by technology area in public filings, so assumptions must be made about their R&D focus areas. In IEA estimates, R&D budgets of companies that are active in multiple sub-sectors are allocated on the basis of the share of revenue in these sectors (including non-energy sectors), complemented by interviews with major companies and details in corporate annual reports in some cases. These attempts to capture only energy-relevant R&D budgets are particularly important in the case of companies whose primary sectoral classification is not well-aligned with the full extent of their market and innovation activities. The Bloomberg Industrial Classification System (BICS) is used for this exercise. This methodology makes it challenging to capture corporate research into energy efficient buildings, appliances and industry, where the energy efficiency or electrification-related R&D activities of these other sectors cannot be separated from their other research activities. However, given the importance of the automotive sector to energy R&D, an informed assumption of two-fifths of R&D being energy-related is made based on interviews and patent filings.

Non-listed companies comprise a non-trivial component of total energy R&D spending and these are not captured by the methodology.

Venture capital

Data on the founding years and fundraising of over 12 000 energy-related start-ups, as well as the associated deals involving over 27 000 investors, are derived from commercial datasets produced by The Cleantech Group and Crunchbase. The dataset includes start-ups founded since 1990 and funding rounds since

2000. Inclusion as an energy-related start-up is based on a reasonable interpretation that a company's primary business objectives include making energy supply or consumption cheaper, more efficient, more environmentally friendly or more secure. The threshold between early-stage and growth-stage deals is set between Series A and Series B. Growth stage includes all private equity finance for start-ups before they a publicly listed or acquired. Debt, grants and share sales are not included.

To keep the analysis focused on energy technology innovation, start-ups have been excluded that are not seeking to commercialise their own intellectual property but are raising funds to deploy third-party technologies (unless otherwise specified). This was not the case in previous IEA analyses, which included a non-comprehensive set of such start-ups.

Certain assumptions underpin the analysis, including: that multiple investors involved in a single deal share the total deal value equally; that if a Seed or Series A deal has a monetary value that is greater than 90% of growth stage deals in that segment, it is more appropriate to classify it as a growth stage deal.

The technology classification for venture capital data matches the 2025 edition of the IEA Energy Technology Classification with only one significant difference: the work of start-ups developing electrochemical batteries is all allocated to energy storage and not divided between electric mobility and energy storage. A deviation from the main classification is used for certain analyses where lithium-ion and sodium-ion battery technologies have been grouped with electric mobility technologies.

Patent data

Patent data analysed and presented in the report is provided by the European Patent Office (EPO). There are three different ways that the data are classified, according to the required level of detail.

- Global and regional data on overall energy technology patents, split by fossil fuel and low-emissions technology categories, are generated by EPO from non-publicly available datasets. This is based on a methodology presented in the 2021 IEA and EPO report Patents and the Energy Transition.
- Global and regional data on energy technology patents, split into constituent energy technology areas is derived from PATSTAT, following processing by the OECD, and based on the international Y02 and Y04S tagging system, as well as the IEA and EPO methodology for identifying fossil fuel patents. Fractional counts are used to ensure that technology and country shares add up to 100%. The latest PATSTAT data are not as up-to-date as the overall figures for all energy technologies.

- Global and regional data on individual technology areas are derived from PATSTAT using dedicated search strategies developed by the IEA (nuclear fission, fusion energy, critical minerals), IEA and EPO (batteries, electricity grids, hydrogen) or EPO (solar PV).[32] Fractional counts are only used with each technology area and not in relation to overlapping technology areas.

Innovation highlights, Races to First and Technology Readiness Levels

A combination of qualitative and quantitative tracking of energy technologies is undertaken within the structured in-house architecture of the IEA ETP Energy Technology Guide. This data framework contains information related to technology descriptions, recent advances, projects in the Races to First in Energy Innovation and technology readiness levels (TRL) for 640 technologies. The IEA ETP Energy Technology Guide was revamped for 2026 to align with the 2025 edition of the IEA Energy Technology Classification.

The IEA ETP Energy Technology Guide is updated annually by IEA expert analysts based on desk research, the State of Energy Innovation survey (see below) and stakeholder input. Where appropriate, changes are reviewed by IEA Technology Collaboration Programmes. New entries are added to the Guide each year when the IEA Secretariat undertakes a dedicated project in an area that is under-represented in the Guide, such as the focus chapters of The State of Energy Innovation report.

Each technology entry in the IEA ETP Energy Technology Guide has an associated TRL that represents the highest level of successful operation achieved for that technology category anywhere in the world. The TRL scale is an established and well-known system for tracking progress of a technology towards its real-world application at full-scale. While it is sometimes difficult to compare between technologies that have different characteristics, the use of TRLs in the Guide allows technology maturity to be placed in a cross-sectoral context. Each TRL upgrade in the Guide is associated with a reported event and hyperlink as supporting evidence.

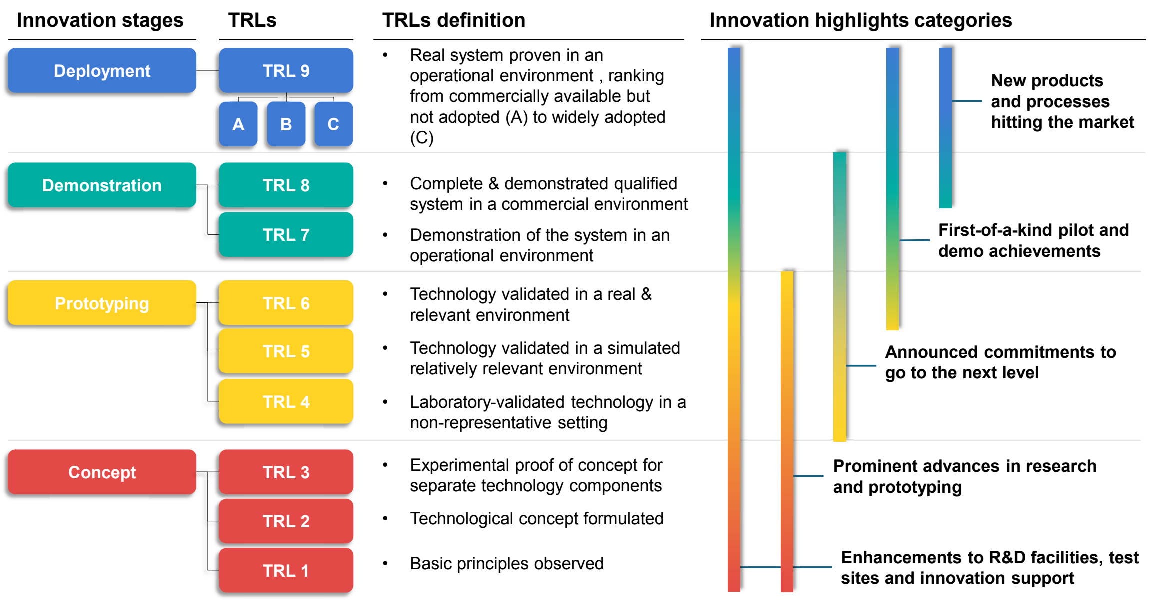
The TRL scale is the basis for the classification of innovation highlights and Races to First phases in the report. However, the purpose of these two exercises is to communicate progress in a more accessible manner than using the TRL scale in full. In particular, some milestones to be communicated do not relate to TRL stages, but are nonetheless important signs of progress, such as the achievement of financial close for a project or the launch of a new product on the market. Some

[32] These strategies use combinations of Cooperative Patent Classification (CPC) codes and keywords and are available upon request to energyinnovation@iea.org.

simplifications and aggregations are necessary. For the innovation highlights, TRLs relate to the five categories as follows:

- **Prominent advances in research and prototyping**. Completed, verifiable achievements from early-stage research, laboratory validation and prototype development, from **TRL 1 to TRL 6**, including gains in performance, durability and efficiency, cost reductions. These milestones generally reflect the transition from theoretical work to physical demonstration and provide the first evidence that a technical pathway is feasible. The result must be specific and documented, for example through a peer-reviewed publication, a laboratory test report or a prototype performance assessment.
- **First-of-a-kind pilot and demonstration events.** Completed milestones from **TRL 6 to TRL 9** that show new operational evidence at scales relevant for future deployment. These results clarify technical feasibility, system integration needs and operating constraints, and provide renewed confidence at a time when related areas are facing slower project development, rising costs and policy uncertainty. "First-of-a-kind" means that the achievement represents a new scale, a new system configuration or a new sectoral or regional context for that technology. The milestone must be fully realised, for example, commissioning, verified stable operation over a defined period, or completion of a structured test programme. Announcements or planned activities are not included.
- **Announced commitments to go to the next level.** Do not represent a technical or commercial milestone already achieved but indicate that project proponents have committed capital or long-term obligations (i.e. have a stake in the outcome) that make subsequent progress to the next TRL level from **TRL 4 all the way to TRL 9** credible. Includes financing agreements, offtake contracts, final investment decisions, joint ventures or company creation that provide new resources and responsibilities.
- **New products and processes hitting the market.** These highlights relate to **TRL 8 or 9** technologies. They show that developers have succeeded in converting technical readiness into a commercial value proposition and are taking the risk of marketing their product to potential consumers. Includes the commercial launch of consumer products, industrial equipment, manufacturing lines, services or licensed processes that have been validated in real operating conditions.
- **Enhancements to R&D facilities, test sites and innovation support.** Can relate to **any TRL level** as they do not fit well into the TRL scale but nonetheless are essential developments that facilitate TRL upgrades, potentially in a range of different technology areas. They form an important but often underrepresented part of the innovation landscape. They strengthen the core infrastructure needed to lower development costs for innovators and produce comparable performance results across multiple stages of technology development. Includes announced investments in new or upgraded facilities that strengthen the infrastructure supporting energy-technology innovation.

Mapping TRL levels to IEA Innovation highlights categories



The [Races to First in Energy Innovation] framework is not based on the TRL scale. It cuts across several technologies, contrary to the Energy Technology Guide or Innovation highlights, which are structured around a single technology entry. Most of the Races are designed to reflect the achievement of TRL 9 and establishment of technical viability under real-world conditions. As a result, the phases preceding the completion of the Race are largely post-TRL 7 because the planning and execution of a full-scale project requires a large pilot to have already been successfully operated. However, this is not the case for all Races. Some, such as *Biochemical improvement of CO_2 assimilation*, are at an earlier stage than TRL 7 today. For others, such as those for small modular nuclear fission reactors and next-generation geothermal, the test of the technology's potential is its ability to be deployed repeatedly and in new locations. In these cases, completion of the Race is beyond the global TRL 9 milestone.

Selecting innovation highlights

Innovation highlights featured on the IEA website as part of the State of Energy Innovation material represent an extract of events from the IEA's ETP Energy Technology Guide updates. The extract includes all events from the past year that IEA experts judge to be a demonstration of progress at the technology frontier in an area with significant future potential to influence how the global energy system develops in future. Each one has supporting evidence that is accessible online to corroborate any claims of what has been achieved. Inclusion in the highlights makes no claim about future impact or potential.

A subset of these highlights are included in the report itself as a means of communicating the breadth and level of progress over the past year. This subset has been selected by IEA analysts to represent a range of technology areas and countries. A level of evenness between the five categories is ensured through this selection.

As a group, these highlights are intended to inform readers about developments in sectors and countries that they may not follow closely, and for which they may not be aware of the state of energy innovation. In each case, however, the highlight is considered to merit its inclusion for its significance and the magnitude of the step taken by the project team. For 2025, attention was also given to highlights that show continued momentum in technology areas where project development has slowed and risk perceptions have increased. These signals help preserve technology optionality, sustain supply chains and enable further technical progress despite weak near-term market conditions.

Allocating contenders to Races to First

IEA experts have allocated projects to the three phases of the Races using the following rules of thumb:

- **Phase 1: Testing at a smaller scale or in different configuration**. Project under preparation or operation does not meet full criteria, such as scale or number of locations.
- **Phase 2: Raising funds and preparing for next phase**. Evidence exists that the project developers have raised some funds or are in serious financing discussions for the named project, which is designed to meet all criteria. For project teams that have stepwise approach through phases at different scales, the move to Phase 2 cannot happen when a Phase 1 project has not yet been completed. In the case of a Race requiring operation in multiple locations or a new location, the project under preparation must be the one that would complete the achievement of all criteria.
- **Phase 3: In construction and could meet criteria**. There must be evidence of a final investment decision for a project that is designed to meet all criteria. For example, there must be credible information to indicate that the financing is in place for the necessary scale, and not only a smaller project with the potential to be expanded in future. In the case of a Race requiring operation in multiple locations or a new location, the project under preparation must be the one that would complete the achievement of all criteria.

How the IEA uses the TRL scale

For the TRL scale to be relevant and useful for a wide range of energy technologies, some additional conventions have been added by the IEA to the original framework developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s. One such addition in 2025 is the application of three post-TRL 9 stages to illustrate whether the technology has market momentum or is struggling to translate technology readiness to commercial relevance.

The IEA application of the technology readiness level (TRL) scale

TRL	Definition	Application to large chemical- or mechanical engineering-based hardware	Application to mass-manufactured hardware	Application to software and digital energy technologies
1	Basic principles observed	The fundamental properties of a potential, not yet clearly defined, technology have been observed and reported. Basic research activities are conducted, and the principles and findings are published in the literature.		-
2	Concept and application have been formulated	The theoretical relevance of the concept has been formulated. Applied research has been conducted, focusing theory and scientific principles on a specific application area. The characteristics of the application are described, and analytical tools are developed for the simulation or analysis of the application. No experimental proof of concept.		
3	Critical functions proven experimentally without all components integrated	Analytical studies and laboratory-scale experiments have physically validated the analytical predictions and feasibility of separate elements of the technology. Components are not yet integrated into a complete system. For example, battery studies using half-cells, redox reactions, electrolyte stability.		Scientific feasibility is demonstrated through development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data.
4	First prototype successfully tested in non-representative conditions	The technology as a whole has been validated in a laboratory environment, with basic technological components integrated to establish that they will work together, sometimes involving special-purpose components unsuitable for scale-up in their current form. Generally, tests are carried out on a very small scale (e.g. output in the range of 10 kJ or tens of grammes), and/or within a limited timescale. Low fidelity compared to the eventual system.	A basic research cell or miniaturised mock-up has been validated in a laboratory environment but not yet integrated into a standalone unit in its proposed final form. Basic technological components have been integrated to establish that they will work together. Tests are still conducted in isolation or in non-representative conditions, equivalent to the start of "A-series" for batteries (lab-scale isolated cell).	Basic software components have been integrated in an isolated environment to establish that they will work together. These are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues.

5	Integrated components proven in representative operational conditions	A prototype has been tested in a representative simulated environment. Basic technology elements have been integrated with elements conforming to the target environment and interfaces. However, the simulated environment may differ from the expected operational environment, and the timescale and outputs can remain small.	The first standalone unit has been operated successfully with auxiliary systems. A prototype has been tested in a representative simulated environment or at a slightly smaller scale than the anticipated final size. Basic technology elements have been integrated with elements conforming to the target environment and interfaces, equivalent to the start of "A-series" for batteries (must be safe and closely match the final design in performance and geometry despite being at a production scale of just a few hundred cells).	Experiments have been conducted with simulated but realistic interfaces to existing systems, simulated problems and in an environment that conforms to the expected commercial setting. System software architecture established. Algorithms run on processors with characteristics expected in the operational environment.
6	Prototype proven at a representative scale and in conditions to be deployed	A prototype has been engineered and tested in a near-desired configuration in a real environment. The technology has been partially integrated with existing systems, outside the laboratory, for an extended period. For example, around 100 hours of operation at the size of a shipping container (roughly 100x smaller than a full-scale unit.	An integrated version of the product has been built and operated successfully outside the laboratory at the expected scale at which the technology will be manufactured, incorporating all active components in a real, non-simulated environment. Equivalent to "B-series" in battery development (cell design becomes unalterable). Further modifications are likely to come from commercial and manufacturing considerations.	Engineering feasibility of a software technology has been demonstrated. A prototype has been implemented on realistic problems in which the software technology is partially integrated with existing hardware and software systems. Test durations smaller than those of full-scale applications.
7	System demonstrated sufficiently to move to full-scale	A working model of the whole process has been demonstrated in close-to-commercial conditions and scale, and for a duration sufficient to demonstrate performance that justifies proceeding to TRL 8. Normal commercial feedstocks have been used, and output has been	Manufacturing capability has been demonstrated by production of systems, subsystems or components in a representative environment. The first examples of the product have been produced without serial production techniques and tested in real-world applications (e.g. a battery in a	Program-level feasibility of software has been demonstrated in a near-commercial configuration and scale. Critical technical risk functionality has been demonstrated and integrated with relevant hardware or software systems has been tested.

		successfully tested for suitability by potential consumers. The demonstration has been made in an operational environment under limited conditions, such as field tests, and integrated with ancillary systems. For example, at a scale that is roughly 10x smaller than a final-scale unit for around 1 000 hours connected to the grid, with multiple start/stop cycles.	car) for enough time to confirm that it can be scaled up to serial production. Equivalent to “C-series” in battery development (manufacturing and testing at a scale tens of thousands of cells).	
8	Commercial scale realised in real-world environment	A unit of the same size as planned for most real-world projects has been constructed and successfully commissioned in real-world commercial and regulatory conditions. For example, if a commercial plant requires four identical units or modules to be installed, one of these has been commissioned. The technology has been fully integrated with operational hardware and software systems Training documentation and maintenance documentation are completed.	The first products have come off a production line (such as a pilot line) in a format that is saleable, and they have been installed by users in real-world conditions. Production yield and quality might still be below the standards needed for profitable large-scale production. Equivalent to the beginning of “D-series” in battery development (scale from 100 000 to 10 million cells per day for commercial use).	Software has been fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenario. The environment is sufficiently realistic to be considered commercial.
9A **9B** **9C**	Successfully operated and commercially available with technology guarantees. Ready for further learning-by-doing.	The system has achieved operational experience and operations have been refined and adapted with operations and maintenance feedback. Around 10 000 hours of use have been logged, or an equivalent duration sufficient to reduce technological risk to a level that is bankable and shows compatibility with all relevant regulations and supply chains. From a purely technical standpoint, the technology can be	Positive feedback from users and the achievement of relevant certifications have allowed production to be scaled up and to begin serving relevant clients. There are no longer any technological risks related to the production equipment, and production could in theory scale up in factories located anywhere in the world. This is equivalent to battery producers having received	Software is readily repeatable and reusable, and fully and easily integrated with relevant hardware and software systems. All software documentation has been verified, and software engineering support is in place.

	integrated into different commercial contexts with performance guarantees, and remaining challenges are commercial, financial, infrastructural and regulatory.	“production part approval” for automotive applications.	
	9A. With few customers and installations, the technology has limited operating hours and limited geographic diversity. **9B**. With multiple operating references, growing operational datasets and early replication in new geographies or markets, residual risk is reduced and there is greater investor confidence. **9C**. Extensive, long duration, multi context operational experience, fully established supply chains, and broad commercial adoption.		

Stakeholder survey

The survey to support this report was anonymous. It was conducted online with a non-public link to the survey shared by email between November 2025 and January 2026.

Questions asked

Section 0

- **In which country are you based?**
- **For which organisation do you work?**
- **Which sector best describes your expertise?** *(Business development and strategy; Engineering and project development; Entrepreneurship; Finance; Research; Government; Other)*
- **Do you have an institutional connection to the IEA?** *(I work for an IEA Member government; I work for an IEA Accession or Association country government; I am a Technology and Innovation Advisory Board member; I am a Technology Collaboration Programme (TCP) member; I do not have direct institutional connection to the IEA).* If you are a member of a TCP, which TCP?

Section 1. Global progress

Please answer the questions in this section with a broad view of energy technology innovation, based on your understanding of the general situation.

Energy technology innovation refers to activities involving technological risk (from basic research to prototyping to early commercialisation) with the aim of providing improved or cheaper energy services (cooling, heating, light, mobility, industrial production etc.) or mitigating the environmental impact of the energy sector

- **How do you judge the current global rate of progress with energy technology innovation compared to the previous year?** *(Unchanged; Better than ever!; Efforts are too diversified, and no technology receives enough support; Plenty of money but too few real-world impacts; Impressive progress despite poor policy support; The rate of progress is about the same as in 2024; I cannot judge the progress; It's slowing down too much; Efforts are too concentrated in a small number of places).* Feel free to briefly share your reasoning for the answer above.
- **What do you think is the more important driver of energy innovation efforts in 2025?** Please rank only your top three, by dragging them up and down. Please look beyond the (often primary!) driver of directly making money from an invention. *(Reduce greenhouse gas emissions; Create new or better jobs; Improve pollution and health outcomes; Support equality of opportunities and social welfare;*

Improve the lives of consumers; Enhance energy security; Improve national economic performance; Expand energy access; Reduce the costs of equipment and energy)

- **How do you judge the opportunities for international co-operation on energy technology R&D and demonstration projects compared with the previous year?** *(Many more opportunities; Slightly more opportunities; No change; Slightly fewer opportunities; Many fewer opportunities; Don't know)*

Section 2. Innovation highlights

In this section we would like to collect a list of announcements, items or events you think we should include among our highlights in energy innovation for 2025.

Before answering, please familiarise yourself with the format of the IEA Highlights in Energy Innovation, which inform The State of Energy Innovation report. Where they represent a change of Technology Readiness Level or major project step forward, the highlights inform the IEA Energy Technology Guide, and Races to Firsts tracker.

You may suggest highlights since late 2024 from any energy-related technology area across the following categories: new products and processes hitting the market; announced commitments to go to the next level; prominent advances in research and prototyping; first-of-a-kind pilot and demo achievements; enhancements to R&D facilities, test sites and innovation support.

- **Please propose up to three highlights from your area of expertise or any other, with hyperlinks wherever possible** *(What event or announcement impressed you? Which is the most relevant technology area for this highlight?)*

Section 3. Trends in your area of expertise

This section looks only at your own area of expertise. If you have several areas of expertise, or if you find yourself straddling two sectors on our list, you can adjust your answers to all the sectors that apply to you.

- **On which technology area do you mainly work?**
- **Which sub-area(s) best define your expertise?** Please select at most 3 options.
- **How do you judge the current rate of progress with energy technology innovation in your area compared to the previous year?** *(Efforts are too diversified, and no technology receives enough support; Impressive progress despite poor policy support; Unchanged; Better than ever!; Efforts are too concentrated in a small number of places; The rate of progress is about the same as in 2015; It's slowing down too much; I cannot judge the progress; Plenty of money but too few real-world impacts)*

- **In your field of expertise, is there a technology area that you think holds particular promise if it can be successfully commercialised?**
- **In your field of expertise, is there a technology area for which you are concerned that progress is moving too slowly?** Please share any thoughts on how the situation could be improved.

Section 4. Policy and finance

In The State of Energy Innovation, we showcase recent policy developments that address key barriers facing energy innovators, especially developments that are creative or potentially high impact in their domestic contexts. We are looking for examples since late 2024 that we can showcase in the next edition.

- **Are there any government policy or funding updates from 2025 that are examples of good practice or progress?** We are interested in all measures, including those that support first-of-a-kind projects, target R&D to new priorities, are tailored to emerging and developing economies, encourage entrepreneurship, or evaluate innovation policy impact
- **Are there weaknesses in available policy support, funding and finance that you would like to bring to our attention?**

End of survey - guidance to the IEA

If you have recommendations on priority areas for the IEA to address in the next 2 years to foster faster progress in technology innovation, please specify them below

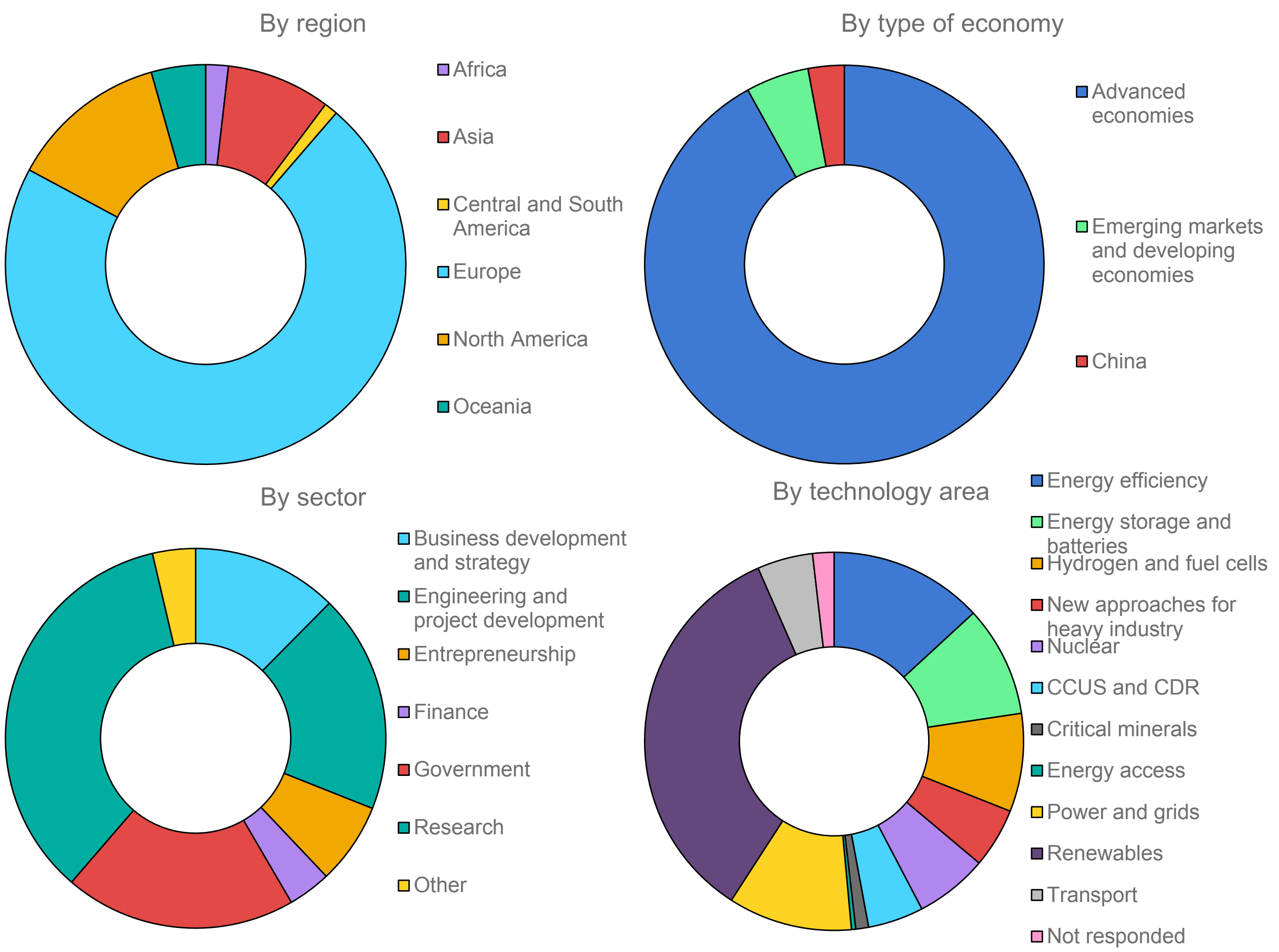
List of energy technology areas provided in the State of Energy Innovation stakeholder survey

Energy efficiency	Energy storage and batteries	New approaches to heavy industry	Hydrogen and fuel cells	Nuclear, CCUS, CDR, methane, critical minerals, energy access	Power and grids	Renewables	Transport
Building design, envelope and passive systems	Thermal storage	Near-zero emissions steel	H_2 production	Nuclear fission	Physical electricity grid technologies	Geothermal	Aviation
Building controls (incl. BEMS)	Mechanical storage (e.g. flywheel, compressed air)	Near-zero emissions cement and concrete	H_2-based fuels (e.g. synthetic fuel, NH_3)	Nuclear fusion	Digital grid management (incl. VPP, DERMS)	Hydro	Electric vehicles and associated infrastructure
Heating (space, water, industrial)	Battery recycling and reuse	Industrial heat	H_2 storage and infrastructure	CO_2 capture	Emerging power generation technologies (e.g. waste heat to power, NH_3-based)	Ocean	H_2-powered transport
Cooling	Battery maker:	Alternative chemicals feedstocks (e.g. biomass, CO_2)	H_2 fuel cells	CO_2 storage		Solar PV	Shipping and boats
Industrial processes	Battery management system	Other	H_2 end-use applications	CO_2 transport		Solar thermal	Rail
Data centre energy use				Critical minerals		Wind	
Lighting				Energy access		Bioenergy (e.g. biogas, liquid, biorefining, solid, feedstock)	

Note: CCUS = carbon capture, utilisation and storage; CDR = carbon dioxide removal; BEMS = building energy management systems; H_2 = hydrogen; NH_3 = ammonia; VPP = virtual power plant; DERMS = distributed energy resource management system.

Selected detailed results

Survey responses by region, type of economy, sector and technology area



Notes: CCUS = carbon capture, utilisation and storage; CDR = carbon dioxide removal. A total of 274 responses were received.

Survey responses to the question "How do you judge the current global rate of progress with energy technology innovation compared to the previous year?" by region, type of economy, sector and technology area

By region						
	Africa	Asia	Central and South America	Europe	North America	Oceania
Better than ever!	1	6	0	10	1	1
Impressive progress despite poor policy support	1	2	0	30	8	2
Plenty of money but too few real-world impacts	0	2	0	18	2	1
Efforts are too concentrated in a small number of places	0	1	1	9	3	0
Efforts are too diversified, and no technology receives enough support	1	1	0	22	6	1
The rate of progress is about the same as in 2024	2	6	2	62	11	4
It's slowing down too much	0	1	0	14	3	2
I cannot judge the progress	0	4	0	31	1	1

By type of economy			
	Advanced Economies	Emerging markets and developing economies	China
Better than ever!	12	5	2
Impressive progress despite poor policy support	40	2	1
Plenty of money but too few real-world impacts	22	0	1
Efforts are too concentrated in a small number of places	12	1	1
Efforts are too diversified, and no technology receives enough support	29	2	0
The rate of progress is about the same as in 2024	82	4	1
It's slowing down too much	20	0	0

By type of economy			
I cannot judge the progress	35	0	2

By sector							
	Business development and strategy	Engineering and project development	Entrepreneurship	Finance	Government	Research	Other
Better than ever!	3	3	3	0	6	4	0
Impressive progress despite poor policy support	8	8	3	4	3	15	2
Plenty of money but too few real-world impacts	5	3	1	1	4	7	2
Efforts are too concentrated in a small number of places	2	4	1	0	1	5	1
Efforts are too diversified, and no technology receives enough support	2	4	3	0	5	16	1
The rate of progress is about the same as in 2024	9	14	4	4	22	33	1
It's slowing down too much	3	7	3	1	1	4	1
I cannot judge the progress	2	8	1	0	12	12	2

By technology area												
	Energy efficiency	Energy storage and batteries	Hydrogen and fuel cells	New approaches for heavy industry	Nuclear	CCUS and CDR	Critical minerals	Energy access	Power and grids	Renewables	Transport	No response
Better than ever!	2	1	0	1	3	1	0	0	3	7	1	0
Impressive progress despite poor policy support	5	3	3	1	1	2	1	0	6	19	2	0
Plenty of money but too few real-world impacts	2	2	6	2	3	2	0	0	2	3	1	0

By technology area												
Efforts are too concentrated in a small number of places	3	4	0	0	1	1	0	0	1	3	1	0
Efforts are too diversified, and no technology receives enough support	3	3	4	2	3	2	1	0	4	8	0	1
The rate of progress is about the same as in 2024	8	7	7	5	5	4	1	1	10	33	5	1
It's slowing down too much	3	4	2	2	1	1	0	0	1	5	0	1
I cannot judge the progress	10	2	1	1	0	0	0	0	2	16	3	2

Survey responses to the question "How do you judge the current rate of progress with energy technology innovation in your area compared to the previous year" by region, type of economy, sector and technology area

By technology area												
	Energy efficiency	Energy storage and batteries	Hydrogen and fuel cells	New approaches for heavy industry	Nuclear	CCUS and CDR	Critical minerals	Energy access	Power and grids	Renewables	Transport	No response
Better than ever!	6	3	3	2	6	1	0	0	8	16	6	0
Impressive progress despite poor policy support	3	7	5	1	3	2	1	0	4	17	1	0
Plenty of money but too few real-world impacts	1	2	3	1	1	2	0	0	2	3	1	1
Efforts are too concentrated in a small number of places	3	1	2	3	1	0	0	0	2	11	1	0

By technology area												
Efforts are too diversified, and no technology receives enough support	6	4	3	3	4	3	2	0	3	9	1	0
The rate of progress is about the same as in 2024	12	7	3	0	1	3	0	1	9	23	2	0
It's slowing down too much	2	2	3	4	0	1	0	0	0	8	1	0
I cannot judge the progress	3	0	1	0	0	1	0	0	1	7	0	0

Survey responses to the question "What do you think is the more important driver of energy innovation efforts in 2025" by region, type of economy, sector and technology area

By type of economy									
	Advanced Economies			Emerging markets and developing economies			China		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Enhance energy security	78	72	50	6	3	1	3	0	2
Improve national economic performance	28	36	43	1	1	2	0	1	1
Reduce the costs of equipment and energy	67	55	45	1	3	3	1	3	1
Improve pollution and health outcomes	4	10	12	1	0	2	1	1	0
Improve the lives of consumers	7	12	11	2	1	0	0	1	1
Support equality of opportunities and social welfare	1	2	7	0	0	0	0	0	1
Create new or better jobs	6	8	9	2	1	1	1	0	0
Reduce greenhouse gas emissions	46	35	60	1	1	3	2	1	2
Expand energy access	15	22	15	0	4	2	0	1	0

Note: Only the top three responses are shown.

By sector																					
	Business development and strategy			Engineering and project development			Entrepreneurship			Finance			Government			Research			Other		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Enhance energy security	7	13	9	17	13	8	4	5	3	3	4	2	18	14	11	36	25	16	2	1	4
Improve national economic performance	5	5	8	2	4	6	1	2	3	1	1	2	6	12	8	13	13	18	1	1	1
Reduce the costs of equipment and energy	11	6	6	15	12	5	7	2	7	3	2	1	17	13	11	16	12	18	0	3	1
Improve pollution and health outcomes	0	0	1	3	1	5	0	0	2	0	0	0	0	3	3	1	6	3	2	1	0
Improve the lives of consumers	2	1	2	1	4	4	2	0	2	1	0	1	0	1	1	2	5	2	1	3	0
Support equality of opportunities and social welfare	0	0	1	0	0	5	0	1	0	0	0	0	0	1	0	0	0	2	1	0	0
Create new or better jobs	2	1	0	1	1	4	0	0	0	0	1	1	3	1	2	3	5	3	0	0	0
Reduce greenhouse gas emissions	4	5	4	8	9	9	4	4	2	2	1	1	1	5	16	20	12	31	1	1	2
Expand energy access	3	3	3	4	7	5	1	5	0	0	1	2	0	4	2	5	7	3	2	0	2

Note: Only the top three responses are shown.

Annex C. Definitions

Currency conversions

Throughout the report, monetary values are typically 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.

Acronyms and abbreviations

AC	alternating current
ADMS	advanced distribution management systems
AEMS	advanced energy management systems
AI	Artificial Intelligence
ARPA-E	Advanced Research Projects Agency–Energy (United States)
BERD	Business Enterprise Research & Development
BIPV	building integrated photovoltaics
CAPEX	capital expenditures
CDR	carbon dioxide removal
CEN	European Committee for Standardization
CENELEC	European Electrotechnical Committee for Standardization
CfD	contract for difference
CO2	carbon dioxide
CVC	Corporate Venture Capital
DC	direct current
DLR	dynamic line rating
DoE	Department of Energy (United States)
DSO	Distribution System Operator
EIB	European Investment Bank
EIF	European Investment Fund
EPO	European Patent Office
EV	electric vehicle
FACTS	flexible alternative current transmission systems
FLNG	floating liquefied natural gas
GHG	greenhouse gas
GWP	global warming potential
H2	hydrogen
HVDC	high-voltage direct current
IEC	International Electrotechnical Commission

IPF	international patent family
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRR	internal rate of return
ISO	International Organization for Standardization
LCO	lithium cobalt oxide
LCOE	levelised cost of electricity
LDES	long duration energy storage
LFP	lithium iron phosphate
LNG	liquefied natural gas
LMO	lithium manganese oxide
NCA	nickel cobalt aluminium oxide
NMC	nickel manganese cobalt
NRC	Nuclear Regulatory Commission (United States)
NZIA	Net-Zero Industry Act (European Union)
OPEX	operating expenditure
PMU	phasor measurement units
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
RTA	revealed technology advantage
SAF	sustainable aviation fuel
SMR	small modular reactor
STATCOM	static synchronous compensator
TCP	Technology Collaboration Programme
TRL	technology readiness level
TSO	transmission system operator
UKRI	UK Research & Innovation
VC	venture capital
VPP	virtual power plant
WAMPAC	wide-area monitoring, protection and control systems
WIPO	World Intellectual Property Organization

Units

°C	degrees Celsius
A	ampere
AUD	Australian dollar
bar	bar
EUR	euro
GW	gigawatt
GW_e	gigawatt electric
GWh	gigawatt hour
h	hour
Hz	hertz
kA	kiloampere

kg	kilogramme
km	kilometre
kt	kilotonne
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
m	metre
m2	square metre
m3	cubic metre
MA	megaampere
mile	mile
mm	millimetre
MW	megawatt
MWe	megawatt electric
MWh	megawatt-hour
MWth	megawatt thermal
s	second
t	tonne
T	tesla
TW	terawatt
USD	US dollar
V	volt
W	watt
yr	year

See the IEA glossary for a further explanation of many of the terms used in this report.

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Typeset in France by IEA - February 2026
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