IOP Institute of Physics

Unleashing Physics to Power the UK Energy Sector

Assessment of technologies, challenges, strengths and potential

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Foreword

Nothing could be more important than tackling climate change and growing our green economy.

In 2023 over 500 members contributed to our first green economy impact report, 'Physics Powering our Green Economy'. A significant landscaping piece, it set out the central role that physics and physicists play in scaling up a sustainable, globally competitive green economy in the UK. Findings were shared at COP28 in Dubai and with policy makers in Whitehall and the devolved nations to inform national strategies and investment.

2023 also saw the hottest year on record, making it even more urgent that we address climate change. And with growing unpredictability in geopolitics, nations are increasingly focusing on protecting critical infrastructure and supply chains.

The UK Government is driving a *Clean Energy Mission* to harness UK's pioneering clean tech industry to ensure energy security, reach net zero and deliver economic growth.

We want to help deliver this mission. To this end the IOP has commissioned the expertise of its membership, to provide robust scientific evidence on priority technology advancements for nuclear and renewable energy generation as well as energy storage and transmission.

I invite policy makers to make full use of the expert insights set out in this impact report.

In doing so, we will unleash physics to power the UK energy sector, strengthening manufacturing, creating jobs and attracting investment into our industrial heartlands.

Professor Tara Shears FInstP
IOP Vice-President for Science and Innovation
(2023 – 2027)

Foreword

The transition to Net Zero is the defining challenge of our time, offering a transformative opportunity for the UK to lead in clean energy, innovation, and sustainable economic growth. As we strive to meet our ambitious climate goals, the role of advanced green technologies cannot be overstated. From photovoltaics and advanced nuclear reactors to next-generation energy storage and new materials for energy transmission, these technologies are pivotal in decarbonising our energy system, industry, and transport.

I welcome the Institute of Physics' new report, **"Unleashing Physics to Power the UK Energy Sector: Assessment of technologies, challenges, strengths and potential,"** brings together cutting-edge research and expert insights on critical technologies that will drive the clean energy revolution. Achieving Net Zero will require a multifaceted approach, underpinned by science, innovation, collaboration and the practical deployment of these technologies at scale. The report's findings highlight challenges and opportunities in this space, offering an important contribution to the ongoing policy development efforts that will help us achieve our climate goals. By taking a whole-system approach—leveraging the full potential of green technologies across sectors—the UK can decarbonise while strengthening its energy security, creating new jobs, and driving sustainable economic growth.

I encourage all stakeholders—from government, industry, and the research community—to engage with the insights in this report. It provides critical evidence that will help shape the policies and investments needed to accelerate our progress towards Net Zero. Together, we can build a more sustainable, prosperous, and energy-secure future for the UK.

Professor Paul Monks FInstP
Chief Scientific Adviser for the Department for Energy Security and Net Zero

Executive summary

Our first report, Physics Powering the Green Economy, outlined the crucial role that physics innovations and physicists have played in shaping the green economy of today. This second Green Economy impact project report focuses on physics technologies with high potential to transform the UK's energy system in the short term, specifically in energy generation (nuclear power, photovoltaics), storage (batteries) and transmission (high-temperature superconductors). We commissioned expert technology assessments from IOP Fellows and Members to assess the technology status, UK strengths, challenges, and opportunities across these domains.

Key themes emerged from the four technology assessments, underscoring the UK's strengths in research and innovation, international collaborations and a pipeline of spin-out and early-stage companies. However, we also identified challenges hindering the full exploitation of these strengths, including barriers to investment, scaling innovations, access to research facilities, and skills shortages. These findings align with the insights in our IOP R&D Blueprint and Venture capital in physics deep tech reports, which highlights specific investment challenges faced by green technologies.

UK Strengths

- Strong academic research and innovation
- International collaborations
- Growing pipeline of spin-out and early-stage companies

Key Opportunities

1. **Nuclear Expertise**: Capitalise on the UK's nuclear knowledge to drive export opportunities in reactor technologies and related services.
2. **Solar Photovoltaic Technology**: Scale-up UK innovation in solar photovoltaics to boost domestic development and protect national technological advancements.
3. **Battery Technologies**: Increase UK capability in solid-state, sodium-ion and lithium-sulphur batteries to compete in expanding global markets for transport and energy storage.
4. **High-Temperature Superconductivity**: Develop infrastructure for electricity transmission from solar and wind farms to UK demand centres and enhance interconnections for electricity trade with Europe.

Cross-Technology Challenges

Despite these strengths and opportunities, the UK faces several cross-cutting challenges:

- Insufficient investment in dedicated R&D and technology scale-up facilities
- Limited access to cutting-edge research facilities and infrastructure
- Skills shortages in key sectors, particularly nuclear, battery and solar technology
- Risks to the supply of critical materials, with a pressing need for improved recycling and waste management

Actionable Interventions

To address these challenges and fully leverage the identified opportunities, we identified the following actions:

- **R&D**:
    - Develop advanced multiphysics modelling and simulation methods for nuclear reactors.
    - Explore alternative semiconductors with similar performance to c-Si in terms of power conversion efficiency, but reduced cost.
    - Develop ways to achieve higher energy densities, improved safety and reduced cost for next-generation batteries.
    - Find solutions to enhance the mechanical stability of high-temperature superconducting materials.
- **Research and scale-up infrastructure**:
    - Develop multi-sector facilities accessible to both academia and industry, to accelerate development and deployment across energy sectors.
    - Upgrade and expand existing science and technology facilities to enable innovation and increase industry growth.
- **Skills Development**:
    - Strengthen industry-academia collaboration through technician training and joint PhD programmes.
    - Establish national facilities (e.g., nuclear power test facilities, standards centres) as part of UK strategy for comprehensive training and skills development across sectors.
- **Sustainability and Recycling**:
    - Address intellectual property complexities and establish clear guidelines for mineral sourcing, battery labelling, and end-of-life management.
    - Provide incentives for large-scale recycling initiatives and invest in applied research on sustainable recycling methods for photovoltaics and battery technologies.
- **Supply of Critical Materials and Technological Independence**:
    - Strengthen UK supply chains for critical materials.

  - Increase investment into next generation and alternative technologies and materials to reduce dependence on foreign supply chains.
  - Build sovereign UK nuclear data capabilities.

Conclusion

By capitalising on the UK's existing strengths, and addressing the key challenges by actioning the opportunities, the UK can:

- Meet climate targets by accelerating decarbonisation and scaling up low-carbon energy.
- Strengthen grid infrastructure to enhance resilience and energy security.
- Reduce dependence on overseas supply chains and imports of critical materials.
- Ensure the UK retains technological leadership and develops a highly skilled workforce.
- Create high-value jobs, strengthen domestic manufacturing, and contribute to economic growth.

The report chapters on physics technologies, contributors and their affiliations are listed below:

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Background

In 2023 the Institute of Physics (IOP) carried out work on an impact project on Physics Powering the Green Economy. Since the publication of the report there have been rapid changes in both the geopolitical and technology landscape, from the growing importance of energy security[1] and critical materials[2] to the fast-paced advances in artificial intelligence (AI) and the concerns about its energy demands[3] and environmental impact[4].

One of the key messages from Physics Powering the Green Economy was that there are no silver bullets: tailored strategies for physics R&D, business innovation, infrastructure and skills are needed to achieve a sustainable and just energy transition. These strategies should be part of a long term, systems approach to leadership, coordination and delivery. That message remains, but in the context of the welcome 2030 Net Zero commitment, this report addresses the question of what more can be achieved on short and medium timescales by leveraging the power of physics.

We focused on four technologies from the areas of energy generation, storage and transmission that were identified in Physics Powering the Green Economy as near-term, high-probability of contributing to achieving the 2030 Net Zero targets and having strong physics underpinning (see report page 25). These are key technologies in the diverse energy sector based on renewables and nuclear envisaged by the government (Make Britain a Clean Energy Superpower). We partnered with top experts from the IOP membership to produce technology assessment profiles for: nuclear reactors, photovoltaics, batteries and high-temperature superconductors for electricity transmission.

The following chapters of this report identify the R&D challenges and opportunities in each area with a focus on the UK context. This report aims to provide context and translate the technical challenges and opportunities for each area and identify how these technologies can best work together. It also provides evidence for decision makers in helping shape R&D priorities and investment.

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[1] HM Government, Clean Power 2030 Action Plan (March 2025) https://www.gov.uk/government/publications/clean-power-2030-action-plan

[2] National Engineering Policy Centre, Critical materials: demand-side resource efficiency measures for sustainability and resilience (October 2024) https://nepc.raeng.org.uk/critical-materials

[3] IEA, Electricity 2024 https://www.iea.org/reports/electricity-2024/executive-summary

[4] National Engineering Policy Centre, Foundations for environmentally sustainable AI (February 2025) https://nepc.raeng.org.uk/sustainable-ai

Energy generation: Nuclear power

Nuclear power is enabled and enhanced by several areas of physics. This chapter focuses on reactor physics, which is the study of the behaviour and control of the reactor core.

Summary

State of the art

- The demand for nuclear energy is increasing but UK reactor physics capability is lower than it has been in the past and is primarily engaged on the existing fleet of reactors
- If new small modular reactors (SMRs) and advanced modular reactors (AMRs) are to be designed, built and operated in the UK this capability must be maintained in the near term and strengthened in the medium-to-long term

Challenges

- Insufficient access to key facilities and tools
- Barriers to effective national and international collaboration
- Insufficient investment in R&D
- Insufficient strategic oversight at a national level
- The skills shortage that is common across many disciplines and specific gaps in niche areas such as nuclear data

UK strengths

- Strong academic research, with world-leading universities
- Good ties between academia and the nuclear industry
- Regulation suited to the assessment of advanced technologies
- Historic and current experience with a range of reactor technologies

Opportunities

- Developing the UK reactor physics capability will enhance the efficiency, safety, longevity and scalability of nuclear energy; it is crucial for increasing UK nuclear capacity
- Investment can be a driver for economic growth in the UK and an increased export potential

State of the art

As home to the world's first commercial nuclear reactor, Calder Hall, the UK has been a pioneer in nuclear power (see Data sheet Table 1). It was the birthplace of many early innovations in reactor technology, analytical methods and experimental test reactors, which led to nuclear power playing a significant role in the UK's energy landscape for almost seven decades, as shown in Data sheet Figure 1.

At its peak, nuclear power generated up to 25% of the UK's energy demand; however, due to the decommissioning of power stations and the increase in the total energy demand, this has now dropped to below 15%. In 2022, the UK government set an objective to increase the proportion of nuclear power to approximately 25% of all power generation by 2050[5]; this was reinforced in the Civil Nuclear: Roadmap to 2050 published in January 2024[6].

To meet this ambitious 2050 target, the UK must construct a new generation of reactors that leverage advances in safety and efficiency. The UK currently operates AGRs and a single PWR. A new Generation III+ PWR is under construction at Hinkley Point C and another is planned for Sizewell C; but more new build is needed. Next generation reactor designs are being developed in the UK and across the world[7]. These include SMRs and AMRs[6]; this 'next generation' reactor technology is undergoing design assessment in the UK. Near-term increases in nuclear power generation capacity, after Sizewell C, will likely still involve large scale gigawatt plants until the next generation plant designs are finalised.

Compared to older reactor designs, SMRs take advantage of a reduced size and modular build which, when deployed at scale, could dramatically reduce their capital cost. Other advantages include unlocking much more flexibility in siting; allowing power to be generated where it is needed, such as at data centres or heavy industrial sites.

Microreactors, a subcategory of SMRs, could be deployed within urban communities to provide electrical power and district heating benefits, within remote mining communities, military bases, areas hit by natural disasters, or even extra-terrestrially.

There are many AMR concepts which currently have a lower overall TRL than SMRs[8] but offer potential advantages such as allowing a closed fuel cycle, reducing

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[5] HM Government, British Energy Security Strategy (April 2022) https://www.gov.uk/government/publications/british-energy-security-strategy

[6] HM Government, Civil Nuclear: Roadmap to 2050 (January 2024) https://www.gov.uk/government/publications/civil-nuclear-roadmap-to-2050

[7] IEA, The Path to a New Era for Nuclear Energy (January 2025) https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy

[8] HM Government, Advanced modular reactors (AMRs): technical assessment (July 2021) https://www.gov.uk/government/publications/advanced-modular-reactors-amrs-technical-assessment

mineral extraction requirements and potentially reducing waste burdens. They may offer further flexibility in siting, due to the inherent safety of the designs.

Reactor physics is the study of the fundamental physics of the reactor core; specifically, the dynamics of the neutrons forming the chain reaction and their interaction with the reactor components. It is key to demonstrating the safety of the reactor and to optimising its performance and lifetime. It also plays a major role in developing new fuels and core designs.

UK reactor physics capability is lower than it has been in the past and is primarily engaged on the existing fleet of reactors; however, if new SMRs and AMRs are to be designed, built and operated in the UK this capability must be maintained in the near term and strengthened in the medium-to-long term.

Future R&D

Three of the six key challenges outlined by the Reactor Physics Division of the ANS[9] relate to R&D:

1. Develop and generalise the use of advanced modelling and simulation methods and tools useful to the entire community; see 'Analytical methods'. For example, the use of multiphysics methods to model the interplay between neutronics, thermal hydraulics and fuel performance for AMRs. High-fidelity tools and methods could act as a surrogate in place of expensive experimental testing, in some cases, but require verification and validation.
2. Develop a clear strategy, based on technical considerations, regarding management of used nuclear fuel (and other nuclear wastes); see 'Nuclear facilities'. The main options identified for dealing with spent fuel are storage in a repository or using it in nuclear reactors, with the former the current favoured option in the UK.
3. Improve the performance of existing and future reactors, for example, by the application of advanced methods and tools, or by the development of more advanced fuel types such as TRISO fuel. See 'Supporting the existing fleet'.

Analytical methods

Advanced analytical methods, such as computer codes, covering neutron transport and isotopic changes in fuel and structural components, along with associated methods in thermal, fluids and mechanical modelling, are today required to conduct all reactor physics design and safety analysis. The quality and validity of these codes is one of the limiting factors in both supporting the current fleet of reactors and in designing new reactors.

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[9] Reactor Physics Division Nuclear Grand Challenges https://rpd.ans.org/nucleargrandchallenges/

New analytical methods, that take advantage of recent advances in computational power, are being developed in different institutions worldwide, including the UK.

Improved reactor physics methods allow more accurate modelling of existing core designs, improving safety and allowing for conservative assumptions to be removed, leading to more optimised core designs which, in turn, will allow greater and more reliable power output.

Nuclear data

A key aspect for reactor physics is the availability and quality of nuclear data, such as neutron interaction cross sections, fission yields and energy release data. Even after 70 years of experiments and evaluation, key data for fundamental isotopes continue to be revised to a significant degree and other isotopes have little data with significant uncertainty. This is a particular challenge for advanced reactor designs that use new materials and operate at temperatures outside the envelope of older designs. Obtaining new data requires expensive experimental work, modelling and data processing; the time lag between requesting new data and it being available to use is almost prohibitively lengthy.

Nuclear facilities

As indicated in Data sheet Figure 2, historically the UK has invested significantly in nuclear R&D facilities. These facilities were crucial for testing new technologies, validating analytical methods and obtaining nuclear data. However, there are currently no commercially available test reactors or research facilities in the UK; the facilities provided by NNUF do not include such a capability.

Supporting the existing fleet

Before new reactor designs are operational, the existing fleet and new deployments of existing, replicable large-scale reactor technologies will play a vital role in supporting the UK's energy makeup. The fleet of gas-cooled reactors have had their lifetimes extended several times from the original design, benefitting from R&D in, for example, graphite and steels behaviour among many others. The UK's only PWR is currently scheduled for closure in 2035 (40-year life), although the lifetimes of many similar plants have been extended to 60 and even 80 years. Achieving this might require changes to core design, for example with the introduction of new materials and increased understanding of neutron fluence and damage to key components. Increased demand for flexibility, in a changing grid operating profile, could require better knowledge of real-time core conditions while spent fuel could be stored more compactly and economically with increased confidence in its properties.

Challenges

R&D in reactor physics is an essential part of the growth of the nuclear energy sector in the UK. Delivering valuable R&D requires two foundational pillars: increased overall investment, with confidence in continuity of funding and better alignment of that investment across government, industry and academia.

People and skills

The UK reactor physics community faces a serious skills and resource gap. A decrease in nuclear power investment in previous decades, combined with an ageing workforce, has resulted in a dwindling community of professionals. Reactor physics is a technically complex and demanding discipline; it takes many years to develop new professionals into experienced practitioners, but this issue is cross-discipline and has led, for example, to the setting-up of Destination Nuclear[10] to address it.

A strategic view of the long-term staffing levels of the discipline needs to be conducted (inclusive of the growing civil and defence sectors) and recruitment aligned to meet that demand. At the other end of the talent pipeline, consideration must be given to the retention of experienced staff in the face of competition from other high technology industries and retirement. The National Nuclear Strategic Plan for Skills[11] sets out a route map to do this at the industry level, underpinned by the Nuclear Workforce Assessment[12].

In the short term, we need to ensure that there are sufficient skills in shielding and radiation transport modelling to help with the decommissioning of the current fleet. To support the ambitious goals of new nuclear build, developers are already supporting further development of a skilled workforce through such organisations as the National College for Nuclear; however, the UK must continue to invest in attracting and training a new generation of reactor physicists if future goals are to be achieved.

As the UK deploys SMR and AMR technologies in parallel with ‘gigawatt’ plants, the number of university places, as well as the taught curricula must evolve to address the new challenges. Expanding undergraduate programmes, promoting PhD and postdoctoral opportunities and facilitating cross-industry collaboration for training are key enablers. PhD programmes should include advanced reactor physics methods. Industry partnerships should be strengthened to offer real-world research opportunities for students. Some partnerships already exist, but this approach should be broadened

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[10] Destination Nuclear https://www.destinationnuclear.com/

[11] National Nuclear Strategic Plan for Skills Building Skills for the Nation’s Nuclear Capability (2024) https://nuclearskillsdeliverygroup.com/wp-content/uploads/2024/05/NSDG-National-Nuclear-Strategic-Plan-For-Skills.pdf

[12] Nuclear Workforce Assessment (March 2025) https://cogentskills.com/wp-content/uploads/2025/04/Nuclear-Workforce-Assessment-2024.pdf

and strengthened. The National Nuclear Strategic Plan for Skills has a target of quadrupling the number of specialist science and nuclear fission PhDs, which will enable this.

Facilities and tools

New developments in analytic and computational tools are expensive and take time to implement, particularly when coupled with quality requirements of the nuclear industry. These tools rely on nuclear data; the UK nuclear data capability is currently low and highly reliant on other countries.

Challenges also arise from both export and commercial use restrictions, which can limit access to UK users. For example, access to the latest multiphysics modelling methods, which are seen as state-of-the-art, is difficult in terms of these restrictions and the computational hardware needed to run them might not be available to smaller organisations. The lack of commonality in tools, and individual efforts required to overcome supply chain and cost issues can also present a barrier to collaboration between different parts of the UK nuclear industry. These issues could be addressed by either more effort directed to the development of more available UK methods, and/or a common framework to coordinate access to international resources. This would particularly help smaller organisations to become effective in nuclear research.

The UK now operates no commercially available test facilities or reactors. Post-Brexit, access to European facilities has also become more difficult which will become a bottleneck for developing new technologies and justifying new reactor designs. Facilities in the US, while being world class, are difficult to access for potential UK users due to the priority given to US organisations. A strategic decision needs to be made as to the facilities which are needed to support new nuclear builds, and either develop these facilities in the UK or strengthening links with existing international facilities. A UK reactor test facility would provide training for nuclear operators, designers, academics and regulators.

The future of existing Post-Irradiation Examination (PIE) facilities is unclear once the AGRs cease operation. Without PIE of new fuel designs, fuel options are limited to existing designs already well-proven in other counties; possibly delaying the ability to deliver new SMR and AMR designs and thus meet net-zero targets. The current PIE capacity should be reviewed, expanded and pro-actively managed to ensure the required testing can be conducted.

Strategic oversight

There is a need for clearer alignment between the UK Government's aspirations for nuclear power and the priorities of industry and academia. To address this, a comprehensive strategy document or roadmap for reactor physics should be developed, outlining the key decisions required and the role of academia, government (for example via Great British Nuclear), and industry in achieving them. Industry should also play a larger role in aligning and prioritising R&D, ensuring that academic advancements are directly applicable to real-world applications.

The UK should be a nuclear leader in the international nuclear community and improve collaboration with other countries. Building closer ties with global research bodies and nuclear facilities will provide access to additional resources, knowledge, and testing facilities. The UKNNL provides a good example of linking the UK to international research partners, but more collaboration needs to be fostered between UK and international industry.

There are also synergies that could be unlocked by taking a more strategic approach. The UK is a world-leader in fusion technologies where radiation transport modelling (a key part of reactor physics) is vital. Reactor physics is also key in defence, where the AUKUS naval nuclear propulsion programme will require many more reactor physicists; and in the small, but growing, space nuclear sector. A strategic approach would ensure collaborative benefits rather than negative competition for a limited pool of expertise.

Investment

Large investment in the UK nuclear R&D in the 1970s coincided with the development and delivery of new reactors; but this dramatically declined with the lack of new nuclear build, only starting to pick up again in the 2010s. Data sheet Figure 1 shows the overall spending on nuclear-based R&D since the 1980s for the UK, France, Japan and USA. R&D funding is significantly lower than other OECD countries and the levels provided during the last phase of new build in the UK.

UK strengths

The UK has a rich historical legacy in nuclear power and a strong reputation for innovation in reactor physics. This legacy continues to provide a foundation for future advancements in the field. The UK experience in operating AGRs, particularly the high-temperature, heterogeneous and graphite aspects, leaves us well placed to transfer knowledge to next generation designs, if that transfer happens before the existing knowledge is lost.

The UK boasts a wealth of academic institutions with long-standing reputations on the international stage for excellence in research related to reactor physics. Their research and collaborations contribute to a pool of talent and expertise that can support the development of new codes, reactor designs and fuel cycles. The UK has excellent universities and private organisations but the strategic alignment between government, industry and academia, of the type exemplified in the US, is currently lacking.

The UK's nuclear sector is also supported by active reactor physics communities within major organisations. These organisations are at the forefront of supporting the current nuclear fleet, developing SMR and AMR technologies, playing a key role in advancing the country's nuclear ambitions. The UK has regulatory processes that are, in principle, perfectly suited to the assessment of advanced technologies, with the non-prescriptive approach of the ONR allowing flexibility in demonstration of safety.

Potential

Developing the UK reactor physics capability will play a key role in enhancing the efficiency, safety, longevity and scalability of nuclear energy, making it crucial for increasing the nuclear capacity in the UK. The current UK reactor physics capability will struggle to deliver the scale of new nuclear build which has been outlined by the government; however, with investment and more strategic oversight, this challenge can be met.

Nuclear power provides baseload energy (consistent, uninterrupted electricity), which is essential to maintain the stability of the grid, providing a stable baseline as renewable sources like wind and solar fluctuate. With advancements in reactor design, including SMRs, nuclear power stations can be located close to specific industries and help decarbonise power-heavy sectors like AI, steel and cement production that are hard to electrify through renewables alone; high temperature gas reactors are a good source of hydrogen[13]. Both existing large-scale power-plant designs and SMR/AMRs can be modified to be able to supply low-carbon heat as well as electricity. Such heat can be used to further decarbonise hard-to abate sectors.

New nuclear build in the UK will support huge supply chains, offering billions of pounds of investment to UK companies. The worldwide market for new nuclear power is enormous, in the order of trillion of pounds[14]; having a UK product means we can take a part of that prize. These opportunities are only available if there is a saleable UK product, with UK companies making supply chain decisions.

Moreover, the UK can capitalise on its growing nuclear expertise for export opportunities, both in reactor technologies and services such as:

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[13] Connolly, C.et al, Techno-Economic Analysis of Heat-Assisted Hydrogen Production from Nuclear Power. *New Energy Exploitation and Application*, *3*, 108–129 (2024). https://doi.org/10.54963/neea.v3i1.234

[14] NEI, Global Nuclear Market Assessment Based on IPCC Global Warming of 1.5° C Report (July 2020) https://www.nei.org/resources/reports-briefs/uxc-global-nuclear-market-assessment-report

- Providing consultancy services for reactor design, manufacture, deployment and operation in other countries.
- UK as a world class training centre for reactor physics with ‘best-in-class’ facilities.

This can drive economic growth, create jobs and fostering high-tech industries. Investing in nuclear will make the UK a leader in clean energy, bolster energy independence and accelerate its transition to net-zero; reactor physics is a key enabler for this.

Glossary

Term	Description
AGR	Advanced Gas-cooled Reactor; a second-generation nuclear reactor designed and operated in the UK that uses graphite as the neutron moderator and carbon dioxide as coolant.
AMR	Advanced Modular Reactors use new and innovative fuels, coolants, and technologies to generate low carbon electricity, and take advantage of the same modular-build principles as SMRs. Many designs have the potential for a range of applications beyond low-carbon electricity generation, including production of hydrogen, direct heat for industrial or domestic use and nuclear waste management solutions.
ANS	American Nuclear Society: an international, not-for-profit organisation of scientists, engineers, and industry professionals that promote the field of nuclear engineering and related disciplines.
Closed Fuel Cycle	An advanced fuel cycle with the goal of achieving sustainability by reducing the final waste's radiotoxicity and improving resource utilisation while maintaining its economic viability. Different types of advanced fuel cycles are under research, but most of them are based on the use of AMRs and fuel reprocessing.
Generation III (Gen III)	A class of nuclear reactors designed to succeed Generation II reactors, incorporating evolutionary improvements in design. These include improved fuel technology, higher thermal efficiency, significantly enhanced safety systems (including passive nuclear safety), and standardised designs intended to reduce maintenance and capital costs.
Generation III+ (Gen III+)	An evolutionary development of Generation III reactors, offering improvements in safety over Generation III reactor designs
Generation IV (Gen IV)	Nuclear reactor technologies under development as of approximately 2000, and specifically the six candidate technologies selected by the Generation IV International Forum (GIF) – an international organization that coordinates development. The UK government refers to Generation IV reactors as AMRs.
Nuclear Data	Data libraries compiled from processed experimental measurements of reaction cross-sections, such as the probability of a specific reaction taking place.
ONR	The Office for Nuclear Regulation, the UK's civil nuclear regulator.
PIE	Post-Irradiation Examination: the study of used nuclear materials, such as nuclear fuel, to understand the failure modes which occur during normal use and, hence, how it will behave during an accident. This information is also used for quality assurance, in the development of new fuels and supports analytical modelling of through-life performance.
PWR	Pressurised Water Reactor: light-water nuclear reactors that originated for naval nuclear propulsion programmes but now constitute the majority of the world's nuclear power plants; mainly Gen II with some, more recent, Gen III systems.

TRISO	TRi-structural ISOtropic particle fuel; robust and small, each particle acts as its own containment system thanks to its triple-coated layers, allowing them to retain fission products under all reactor conditions. TRISO particles cannot melt in a commercial high-temperature reactor and can withstand extreme temperatures that are well beyond the threshold of current nuclear fuels.
EPR	A Generation III+ PWR design.
Magnox reactor	An early type of nuclear power running on natural uranium with graphite as the moderator and carbon dioxide gas as the heat exchange coolant.
LWR	Light water reactor is type of nuclear power reactor that uses normal water, as opposed to heavy water, as both its coolant and neutron moderator.
NNUF	National Nuclear User Facility

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The contributors included insights from UK reactor physicists, discussed at the Reactor Physics Technical Forum meeting hosted by the IOP in September 2024.

Data sheet

Table 1. Nuclear reactors in the UK. Source[15,16,17]:

Timeline	Generation	Type of reactors	UK (generation dates)
1950s to mid1960s	I	Early prototype reactors Magnox reactors	• Calder Hall (1956-2003) • Chapelcross (1956-2004) • Berkely (1962-1989) • Bradwell (1962-2002) • Hunterston (1964-1990) Dungenss (1965-2006) • Hinkley Point A (1965-2000) • Trawsfynydd (1965-1993) • Oldbury (1967-2011) • Sizewell A (1966-2006) • Wylfa (1971-2015)
1970s to mid1990s	II	Commercial power reactors AGR and PWR	AGRs • Hinkley Point B (1976-2022) • Hunterston B (1976-2022) • Dungeness B (1983-2021) • Hartlepool A (1983-) extended to 2027 • Heysham I (1983-) extended to 2027 • Heysham II (1988-) extended to 2030 • Torness (1988-) extended to 2030 PWR • Sizewell B (1995-)
mid 1990s to 2010	III	Advanced LWRs	None built.
2010 to 2030	III+	EPR	• Hinkley Point C construction started 2018-2019, grid connection planned 2029-2030. • Sizewell C awaiting final investment decision.
2030 onwards	III+	SMRs	Awaiting conclusion of government SMR competition and final investment decision
	IV	AMR	Government investment primarily in high temperature gas reactor technology.

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[15] https://world-nuclear.org/information-library/appendices/nuclear-development-in-the-united-kingdom
[16] https://world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom
[17] https://www.edfenergy.com/about/nuclear/power-stations

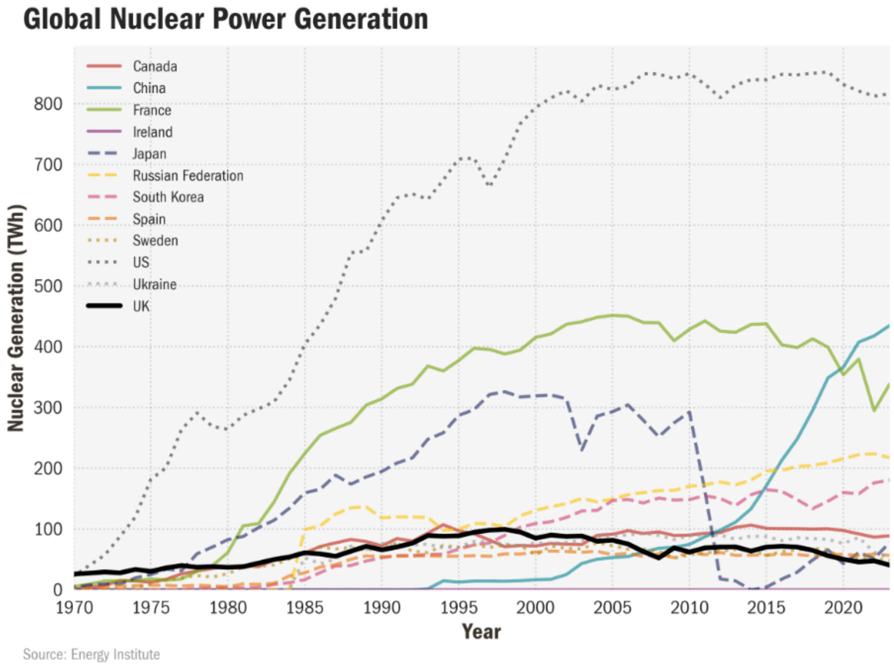

Figure 1 Global nuclear power generation. Data source: https://www.energyinst.org/statistical-review

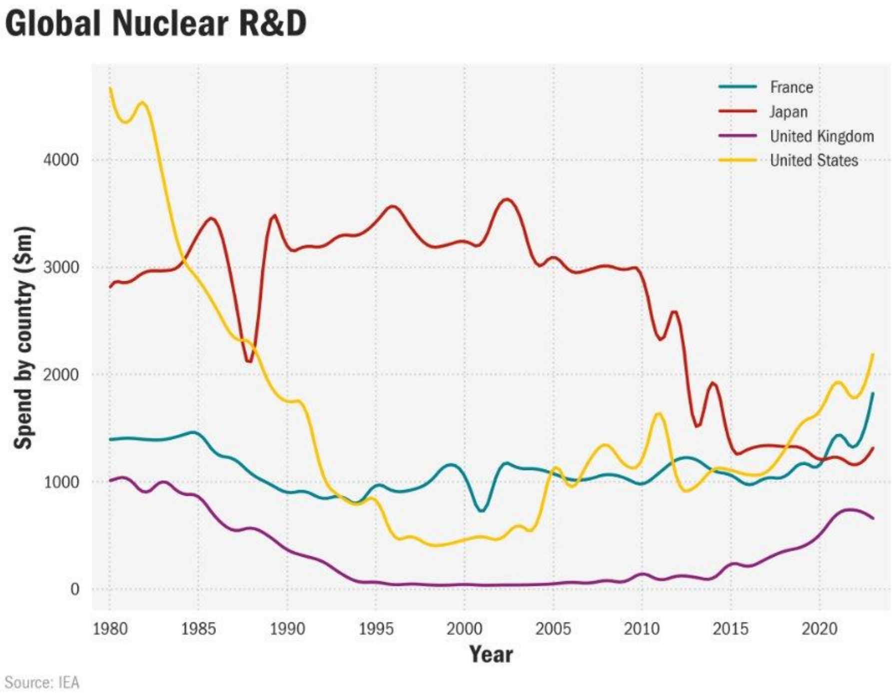

Figure 2 Global nuclear R&D. Data source: https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2#energy-technology-rdd-budgets

Energy generation: Photovoltaics

Summary

State of the art

- Crystalline silicon technology is dominant and strongly growing. Costs continue to go down, but the technology is reaching the limit of its efficiency
- Emerging technologies such as perovskite:silicon tandems offer higher efficiencies and are starting to be commercialised
- Technologies that broaden deployment opportunities or improve integration of photovoltaics (PV) within the energy system can accelerate the renewable transition

Challenges

- China's dominance in manufacturing and overproduction
- Lack of commercialisation support for UK innovation
- Lack of facilities for developing prototypes
- No UK centre for PV R&D
- Regulatory hurdles
- Skills shortage

UK strengths

- Strong academic and innovation record
- Skilled graduates
- Good environment for early-stage commercialisation
- Strong related industries

Opportunities

- Investing in UK PV technology could bring energy security as well as industrial growth. Synergy with battery and network industries: investing in all can accelerate near term decarbonisation

State of the art

Photovoltaic (PV) technology is the means to convert solar radiation into electric power. PV panels are made from layers of semiconductor materials (usually silicon) that harvest light and generate DC electrical power, which is then converted into AC power and fed into the electricity grid, provided directly to an electric load or stored for later use. PV technology has developed strongly with a production growth rate consistently over 25% per annum over the last three decades, to reach a cumulative installed capacity of over 1.6 TWp globally by end 2023 with over 16 GWp installed in UK[18]. In 2024, 5% of UK electricity was provided by PV, second renewable after wind at 30%[19] while over 8% of electricity was met by PV globally[20]. Costs have decreased steadily, mainly through economies of scale and manufacturing innovations in crystalline silicon (c-Si) technology to reach a global average price of $5c/kWh in 2023[21] considerably below the cost of grid electricity in many countries. Theoretical solar generation capacity greatly exceeds global electricity demand and solar generation is bound to grow, both globally and in the UK. Global low carbon pathways that are consistent with well-below-2C temperature rise predict growth in renewable (solar and wind) capacity at an order of magnitude per decade over the next decade and beyond[22]. The current UK targets are consistent with this, with a 2023 target of 70GWp solar capacity by 2025 and a 2024 ambition of 50 GWp by 2030[23]. The UK market is split between ground mounted utility scale solar (solar farms of 100s MWp of capacity) and rooftop solar.

Commercial PV technology is dominated by c-Si, with the leading cell design evolving from traditional BSF architectures through more efficient PERC, Topcon and HJT designs. Technology is mature with module efficiency of up to 25%[24] approaching its practical limit[19]. Other ‘thin film’ semiconductor technologies have been developed and commercialised including polycrystalline silicon, CdTe and CIGS but have been losing market share, even when offering competitive price per Wp, to the dominant c-Si. Lower TRL technologies are motivated by higher efficiency (including tandem cells based on

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[18] Solar power in the UK - statistics & facts (2024) https://www.statista.com/topics/4934/solar-photovoltaic-industry-in-the-united-kingdom-uk

[19] DRAX Electric Insights https://electricinsights.co.uk/#/homepage?&_k=lyor0w

[20] Masson, G., de l’Epine, M., Kaizuka, I., Trends in PV Applications 2024 doi:https://doi.org/10.69766/JNEW6916 https://iea-pvps.org/trends_reports/trends-in-pv-applications-2024/

[21] Blakesley, J. C. et al. Roadmap on established and emerging photovoltaics for sustainable energy conversion. *J. Phys. Energy* **6**, 041501 (2024) DOI: 10.1088/2515-7655/ad7404

[22] IPCC, AR6 Synthesis Report: Climate Change 2023 https://www.ipcc.ch/report/sixth-assessment-report-cycle/

[23] Solar & Energy Storage Manifesto, (June 2024) https://solarenergyuk.org/wp-content/uploads/2024/06/SEUK-Solar-Energy-Storage-Manifesto-2024.pdf

[24] Green, M. A. et al. Solar Cell Efficiency Tables (Version 65) *Progress in photovoltaics* (2024) https://doi.org/10.1002/pip.3867

silicon) or wider deployability. These include both emerging technologies that are approaching market and early-stage innovations (see Future R&D).

Future R&D

c-Si PV is already mature, growing and widely used, but R&D can still advance the state-of-the-art. The impact of PV technology on the green economy transition can be raised through three means that require physics inputs: increased power conversion efficiency; innovations that broaden deployment opportunities; and integration of PV with the energy system.

Efficiency

Efficiencies of c-Si lab cells and modules advance steadily at ~0.5%/year[19] but are expected to saturate at 28% (see[19]). Current advances often concern industrial designs and practices, for example bringing lab scale advances into mass production, (and therefore tend to happen in industry centres that are not in the UK).

R&D continues into alternative semiconductors with the aim of achieving similar performance to c-Si but cheaply (See Data sheet Table 1). Established thin-film technologies such as CIGS (cell record 23.6%) and CdTe (cell record 21.0%) lag in efficiency despite steady advances and the emerging thin films such as lead halide perovskites (cell record 25-26%) could meet Si in efficiency but are currently considered unlikely to also match its durability and overturn the established industry.

The most likely commercial development towards higher efficiency is a two-semiconductor tandem device from affordable materials, such as a tandem with a wide gap, thin-film semiconductor deposited on silicon. By absorbing high- and low-energy photons in separate materials a tandem device can reduce the amount of absorbed light energy that is lost as heat and reach significantly higher efficiencies, if the electronic quality of the two materials and their interface is adequate. A c-Si based tandem solar cell could offer a step-change in efficiency without strongly disrupting the existing industry. Research has explored a variety of processable semiconductors as the ‘top cell’ for silicon including kesterite, amorphous silicon, CdTe, organic and perovskite. UK company Oxford PV reported a record module efficiency of 26.9% for a large area perovskite/silicon tandem in 2024 (see Solar Cell Efficiency Tables (Version 65) and [25]) whereas cells have exceeded 34% (see Solar Cell Efficiency Tables (Version 65)). This active field is very likely to deliver higher c-Si/perovskite module efficiencies. The main obstacle to commercialisation is the unproven ambient stability of the perovskite layer along with concerns about the use of lead. Among other tandem structures, perovskite/perovskite tandems that exploit the tuneability of these

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[25] Oxford PV sets new solar cell world record (May 2023) https://www.oxfordpv.com/news/oxford-pv-sets-new-solar-cell-world-record

processable, but high-quality semiconductors are progressing strongly (PCE 28% see Solar Cell Efficiency Tables (Version 65)). Although the best performing tandems are based on crystalline III-V multijunctions, these are unlikely to be terrestrially competitive without cheaper crystal growth.

In all the above, expertise in the physics of semiconductor materials and devices are key: light harvesting, minimising recombination, improving electrical quality, improving interface quality, understanding and minimising degradation pathways.

Another less mature route to increased efficiency is enhancement of light harvesting using optical coatings that improve photon utilisation, for example, using upconversion (combining low energy photons to generate higher energy photons) or downconversion (splitting high energy photons into two lower energy ones) to concentrate the incident spectrum close to the solar cell's band gap. Enhanced c-Si cell current has been demonstrated using downconversion via singlet fission; similar technology is being commercialised in UK by Cambridge Photon Technology.

Widening the market

Despite the dominance of c-Si PV, the strongly growing market for renewable electricity creates opportunities for lower TRL PV technologies that extend to applications where traditional PV technology may not be easily deployed. Examples include lightweight roofs or, membranes, conformal surfaces, textiles, windows, greenhouses, aerospace and mobile or distributed micropower. These technologies would not compete with c-Si for utility scale power generation market but could expand the market for solar PV. Moreover, the high-throughput nature of the production processes could enable fast learning and ultimate commercial competitiveness for power generation.

Examples of such PV technologies are 'emerging' processable semiconductors like perovskites, inorganic compound semiconductors and organics that are processed from solution or from vapour phase (see Data sheet Table 1). Such deposition may be compatible with flexible as well as flat substrates. For perovskite single junction and perovskite tandems, slot-die deposition on glass is being developed academically and commercially, with intense activity in China including a 29.1% perovskite/perovskite module[26]. Roll to roll (R2R) processing of entire modules offers advantages of scale up, embodied energy and environmental sustainability (when benign processes are used). R2R fabrication of complete perovskite single junction devices with 10% efficiency was first achieved in Swansea in 2023[27].

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[26] Liu, Z., Lin, R., Wei, M. *et al.* All-perovskite tandem solar cells achieving >29% efficiency with improved (100) orientation in wide-bandgap perovskites. *Nat. Mater.* **24**, 252–259 (2025). https://doi.org/10.1038/s41563-024-02073-x

[27] Beynon, D. et al., All-printed roll-to-roll perovskite photovoltaics enabled by solution-processed carbon electrode. *Adv. Mater.* **35**, 2208561 (2023) https://doi.org/10.1002/adma.202208561

Organic semiconductors, now achieving 20% for solution processed cells, are less developed commercially, but strongly researched especially in China where many recent advances were made. Material design, scale up and operational stability are primary research targets for solution processed technology. The alternative of vacuum phase deposition benefits from the OLED industry experience, promising operational stability, and low embodied energy production at scale. It is being commercialised in Germany (Heliatek) with one recent start-up in UK (TerraChange). The technology faces a clear materials challenge: the molecular materials that enable 20% to be reached with solution processed devices cannot be sublimed, so higher performance, low molecular mass alternatives need to be discovered. As well as being compatible with flexible and lightweight substrates, like perovskites, organics are unique in being able to harvest infrared light while allowing visible light to pass, so allowing application on windows and greenhouses.

Regarding physics challenges for emerging PV technologies, proven operational stability is a limitation and needs to be understood at a more mechanistic level, distinguishing chemical, mechanical and light driven processes. In perovskites, alternatives to lead containing materials that show good stability are needed, while for organics, more stable active layer materials and more synthesisable, lower molecular weight molecules are needed. Both materials families are compatible with high throughput material discovery and process optimisation, and this approach is yielding rapid advances in Germany and US[28].

Manufacture from solution is also interesting in terms of technology accessibility. Slot die or R2R facilities can be set up relatively quickly and could enable more decentralised module production, that may be relevant in developing country contexts[29].

Integration

In the near term, mature c-Si PV technology will dominate deployment and innovations beyond cell technology are needed to help maximise its potential contribution. Take-up of PV generation may be limited by several factors, among them the daily and seasonal mismatch of variable generation with electricity demand, limited capacity of the transmission and distribution networks, and perceived competition with other uses of land, such as food production. Although electricity storage can bridge the gaps between supply and demand, storage capacity is expensive, and the mismatch can be minimised by clever combination of different components of the energy system. Strategies include, integrating generation with flexible loads (charging EVs or grid batteries or pumping

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[28] Zhang, J., Wu, J., Stroyuk, O. *et al*. Self-driving AMADAP laboratory: Accelerating the discovery and optimization of emerging perovskite photovoltaics. *MRS Bulletin* **49**, 1284–1294 (2024). https://doi.org/10.1557/s43577-024-00816-4

[29] https://www.sunrisenetwork.org/tea-at-sunrise/

water when generation is high), smart management of demand, building in flexibility to electrical loads (produce when generation is high, cut back when it is low), integrating solar with new types of load (for example electrolysers for hydrogen generation); and of course, more efficient energy use. As different sectors (transport, heating, industry) become electrified, opportunities arise to design the new loads with enough flexibility that renewable generation can be used when available, making use of electrochemical, mechanical and thermal storage and even product storage. See also Data sheet Table 2. Regarding competition for land resources, the integration of PV generation with agricultural land or agricultural operations, 'agrivoltaics' is rapidly developing offering benefits to farmers including energy security, additional income through power export, power for increasingly automated agricultural production and protection of crops from storm or drought[30]. In all these areas, physics-based skills in problem solving and optimisation are very relevant to system design and operation.

A neglected area that will become increasingly important as the first generation of PV panels reach their end of life will be the recycling of PV hardware. With c-Si modules, it is likely that the semiconductors can be re-used while encapsulation and electrical components may be replaced. Physics is relevant both to development of methods to diagnose failures and salvage useful material, and to the improvement of module designs – including designs for emerging PV modules – so that panels can be more readily recycled in future.

Challenges

An outstanding challenge for local commercialisation of PV is the strong state of the PV industry in China and the very different funding mechanisms that operate there.

Huge development of c-Si PV manufacturing in China over the last two decades has resulted in both low module price and the establishment of a massive industry with 80% of PV panels being produced in China and ~95% of silicon wafers[31]. This introduces problems such as overproduction discouraging other countries from developing their own PV production capability[32], and supply chain risks due to overdependence on specific countries. For UK, competing on c-Si module innovation or production is simply not viable under current conditions.

While UK has developed innovative technology independently, such as perovskite on silicon tandems, the development of such technology is proceeding in China, thanks to high levels of state funding for what are seen as important

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[30] Agrivoltaic Systems in England and Wales https://randd.defra.gov.uk/ProjectDetails?ProjectId=21220

[31] Solar PV Global Supply Chains (July 2022) https://www.iea.org/reports/solar-pv-global-supply-chains

[32] Masson, G., Bosch, E., Van Rechem, A., de l'Epine, M. Snapshot 2024, https://doi.org/10.69766/VHRF4040

technologies. UK and Europe have no equivalent funding culture and risk being left behind. In the US, the Inflation Reduction Act has helped stimulate commercial initiatives and even attracted some from Europe. This imbalance in funding availability for energy R&D is a very serious challenge to national commercialisation of technologies, even of local innovations.

Other challenges to commercialisation include the lack of certain facilities for developing prototypes and the lack of a dedicated centre to provide commercialisation support and standardised testing in PV. This is a notable lack considering that batteries, nuclear, quantum and AI technologies have a national centre in the UK, and given the existence of Fraunhofer Institute for Solar Energy Systems (FISE) in Germany and National Renewable Energy Laboratory (NREL) in US that are very active in supporting solar R&D. Trade barriers (such as customs with the EU) increase costs for integrated supply chains and make it harder to overcome gaps such as the lack of tool manufacturers.

UK is no longer a natural choice for manufacturing, thanks to loss of other potentially related manufacturing industries, but it could still retain leadership of its own innovations with better support for businesses. Regarding workforce and skills, while UK has talented graduates, attracting skilled workers is now difficult due to immigration regulations. At the scale-up and deployment level, skills are short and UK lacks an apprenticeship system to build them up. The general shortage of skills in the semiconductor industry is also relevant.

Regulatory issues are often overlooked, but present challenges both for deployment of conventional solar technologies and finding markets for emerging ones. Building regulations, especially following the Grenfell disaster, are limiting the application of building-integrated and building-applied PV. Complicated regulatory procedures add to the costs of system installation and increase risks facing new products intended for building integration. To encourage take-up, regulations could be simplified. Innovations in regulation that enable the sharing of benefits from distributed PV systems with the community could further promote deployment. As well, consistency in PV policies is required for market stability to encourage investment: the UK example of withdrawal of feed in tariffs in 2015 led to a sudden halt in market growth that persisted for 5 years while the global market moved ahead (see Data sheet Figures 3, 4).

UK strengths

UK benefits from a strong track record particularly in the science and innovation of emerging PV technologies (for example early discoveries in organic and perovskite PV and related IP); a traditionally good academic environment with a PV community that has been relatively well connected for the last 20 years, despite lack of a national centre; a talented graduate pool; and an environment that is encouraging for early stage start-ups, given the availability of venture capital funding and small business support mechanisms. The UK environment is thus good for the birth and development of innovative PV technology, but it fails in the larger scale development, upscaling, manufacture, demonstration, and in protecting or promoting national innovations. UK is also strong in relevant industries that include, petrochemicals, glass, coating technology and encapsulation, although it lacks its own supply in some materials and tools. Its strength in certain underpinning industries for example computer science and AI, finance, photonics, quantum technology and its ambitions to grow strength in semiconductors are all synergistic with a growing activity in PV R&D.

Upscaling and commercialisation could be assisted by initiatives to invest in pilot line support, national testing and scale-up facilities, and by regulation that could open up markets for new technologies. Support for such development would also benefit related industries such as chemicals, glass and semiconductors.

Changes in policy and regulation could assist in early-stage deployment of new products, strengthening confidence in markets. Policy changes that could help to raise the value of homes with PV installations could also support the industry.

Initiatives supporting building-mounted PV align well with wider economic and social goals by improving energy resilience, avoiding fuel poverty and supporting local jobs and skills as demonstrated by the Active Buildings Project.

Initiatives that support integration of PV generation with other parts of the energy system, which could be in design of PV generators that are integrated with electrical storage, hydrogen generation, thermal storage, agriculture, communications (for Internet of Things, IoT), industry (for decarbonisation), or greenhouse gas removal, can provide multiple benefits. These include greater and faster penetration of renewables into the energy system and greater energy efficiency, both helping to reduce emissions; support for the related industries; and security in energy supply, all of which can offset the investment cost longer term. Moreover, knowhow and capability in integration of renewables with the energy system so as to increase utilisation of renewable power, improve efficiency and advance decarbonisation will be valuable to the UK and its leadership in accelerating the transition to the green economy.

Potential

Support in the following areas would stimulate the growth of innovative PV technology, the development of UK industry, and the necessary growth in PV deployment to meet the 70 GWp by 2035 target, to help related industry and demonstrate the transition to a fully low-carbon economy.

Support for new PV technology, would include:

- Scale-up of perovskite on silicon or other low-cost tandem designs, to raise efficiency
- Development and scale-up of emerging (such as perovskite or organic) materials technologies to widen deployment, exploiting advances in automation and AI
- Early-TRL photonic technologies to amplify light harvesting that are relevant to photonic applications as well as PV
- Initiatives in design for recycling with both conventional and emerging technologies

Support for PV integration, would include:

- Pilot projects demonstrating integration of PV with other sectors in the energy system, for example PV + transport, PV + hydrogen/synthetic fuels, PV + heat, PV + demand management
- Building-integrated renewable energy systems to demonstrate socio-economic benefits (avoiding fuel poverty, local economy and skills), develop designs and stimulate markets
- Agriculture-integrated PV demonstration projects, to develop system designs, stimulate markets, support agriculture and demonstrate synergy

Support for the UK PV ecosystem, would include:

- Investment in skills and training, a national centre (standards & testing), and scale-up facilities
- Recognition of the co-benefits of PV manufacture and deployment with other industries, such as construction, building materials, transport, energy storage
- Regulatory simplifications, consistent policies
- Technology dissemination via overseas engagement (for example via Ayrton)
- Initiatives to stimulate early product deployment and build local markets

Glossary

Term	Description
PCE	Power Conversion Efficiency is the sum of the electrical power output produced by a solar cell and any additional photovoltage and photocurrent generated.
BSF	Back surface field, The traditional silicon solar cell design dating from 1980s
PERC	Passivated Emitter Rear Contact Cell. A design of crystalline silicon solar cell developed in University of New South Wales that became the dominant commercial technology around 2020
Topcon	Tunnel Oxide Passivated Contact, a structure of a new type of solar cell
HJT	Heterojunction Technology which combines standard photovoltaics with thin-films
CIGS	Copper Indium Gallium Selenide
Roll to roll	A process in which inks are continuously deposited onto flexible substrates. This technology has the potential to enhance throughput and reduce manufacturing costs.
Module efficiency	Is the amount of solar energy which hits the surface of a solar cell and is converted into electricity.
Slot die	A scalable technique for rapidly depositing thin, uniform films

Contributors

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Data sheet

Table 1. Solar cell technologies, applications and technology readiness levels.

Cell technologies	Record PCE Cell (module) %	Comments / Application areas	TRL
Mature PV technologies			
c-Si	27.3 (25)	Dominant and fastest growing PV technology, steadily improving efficiency along with technology evolution (PERC→ Topcon → HJT), steadily falling cost. Utility scale solar based on c-Si is ~ $.05/kWh	9
GaAs	29.1	Highest efficiency for single junction. Developed for space power, too costly or terrestrial use but important as an example of very high efficiency	9
Traditional thin film technologies			
CdTe	21.0	Most commercial thin-film technology. Has undercut c-Si in cost but losing market share, now ~5 %.	9
CIGS	23.4	Promising efficiency but low market share (<1%). Flexible modules commercialised	9
Emerging semiconductor technologies			
Perovskite (single junction)	25-26	Innovative PV technology, rapidly improving efficiency, compatible with deposition from solution or vacuum. Limited by ambient stability and concerns about Pb content	3-4 (vacuum)
Perovskite/Si (tandem)	34.6 (29.6)	Leading option for efficiency enhancement of c-Si based technology. Record module efficiency (and IP) held by UK company Oxford PV	8 (Oxford PV)
Perovskite/perovskite (tandem)	29	Potential competitor with other tandems such as perovskite / c-Si	5-7
Perovskite R2R (single junction)	10	Fully solution processed roll to roll process developed at Swansea	5
Organic (single junction, solution)	20	Innovative PV technology, potential for semi-transparent modules. Highest efficiencies achieved with solution processed	1-3

		materials, but not currently scalable	
Organic (tandem, vacuum)	13	Vacuum deposited technology is scalable and very low carbon, but currently lower efficiency	3-4
Optical coatings: Traditional anti-reflection or anti-glare coatings improve overall performance, TRL 9 Innovative coatings to shift the solar spectrum and raise efficiency, TRL 1-3			

Table 2. Photovoltaics integration opportunities

PV Integration opportunity	Status	Advantages or challenges
Utility scale	Mature, large market	Can be limited by network capacity; perceived or real competition for land use. Can integrate with grid storage.
Rooftop	Mature, large market	Can be limited by network capacity but offset by local loads; stimulates flexible demand. Can integrate with domestic or local community storage.
Transport	Growing market	Effective use of EV batteries as storage is a win-win for both sectors, intrinsically flexible loads enable greater penetration and reduce pressure on network
Fuel production	Emerging market	Synthetic fuel such as hydrogen production requires abundant renewable electricity. Integration of PV with electrolysis will improve costs and can introduce load flexibility
Agriculture	Emerging market in UK, growing elsewhere	Agriculture integrated PV provides power for agricultural operations, energy security and income for farmers, protection for crops from drought and storm, and reduces competition for land use

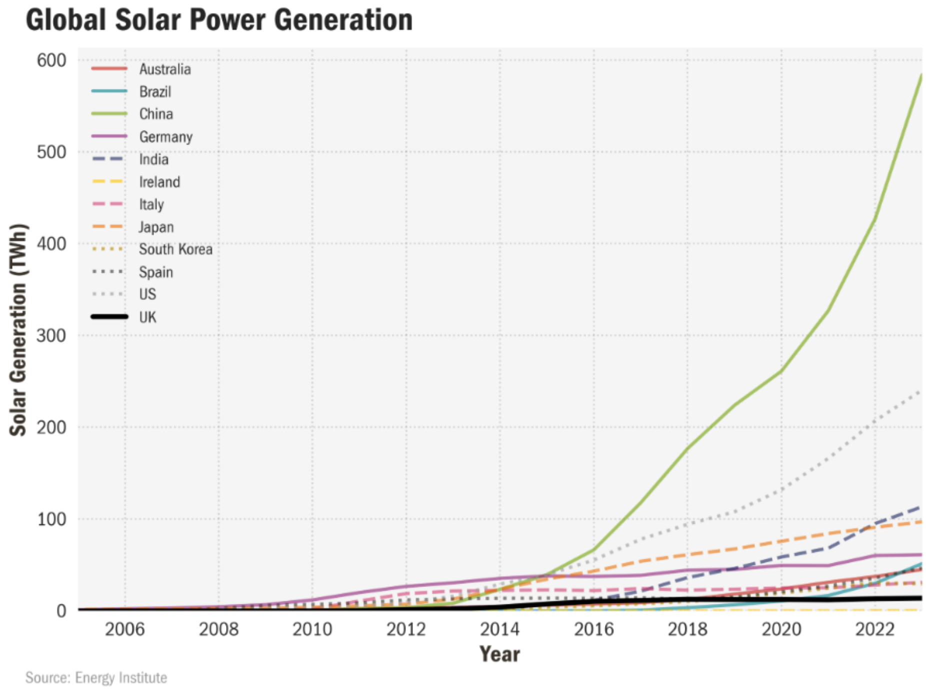

Figure 3 Global solar power generation Data source: https://www.energyinst.org/statistical-review

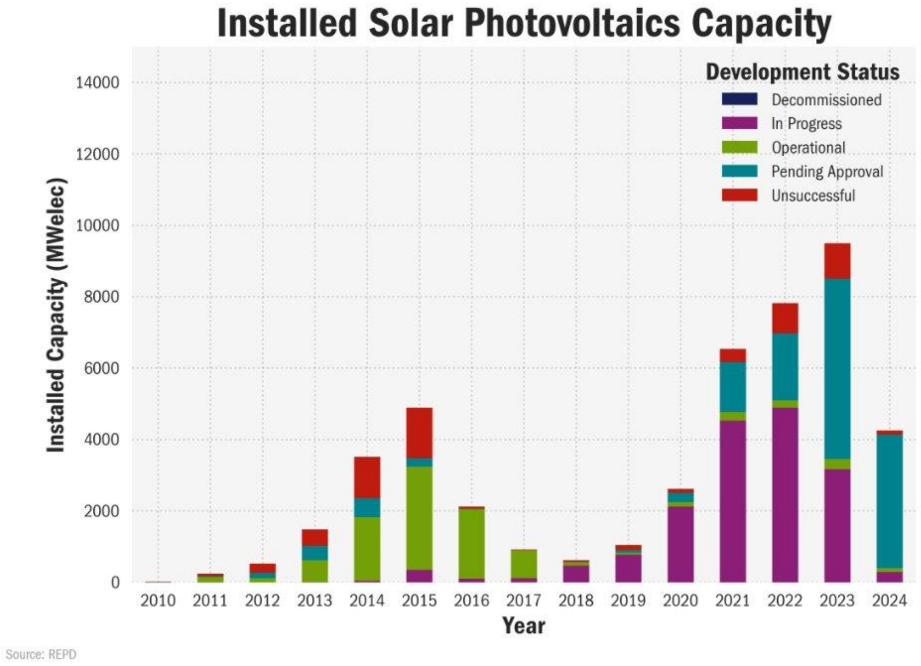

Figure 4 Installed solar PV capacity Data source: https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract

Energy storage: Batteries

Summary

State of the art

- Lithium-ion batteries are the dominant technology; costs going down, but the technology is approaching performance limits
- Next-generation battery technologies are at lower TRLs; advancing them requires cost reduction as well as improvements in energy density, safety and recycling

Challenges

- Access to research infrastructure
- Supply chains vulnerability
- High capital costs and uncertain investment climate
- Skills shortage
- Regulatory uncertainty

UK strengths

- Startups and innovation systems
- Pipeline in gigafactories investment
- Expertise in next-generation batteries and early-stage R&D
- Strong academic institutions and collaborations

Opportunities

- Scaling battery manufacturing
- Long-term R&D in solid-state, sodium-ion and lithium-sulphur
- Enhancing grid resilience; developing long-duration storage

State of the art

Energy can be stored in chemical, electrical, mechanical, electrochemical and thermo-mechanical systems. Electrochemical energy storage, more commonly known as battery technology, is essential for decarbonising transport through the transition to electric vehicles (EVs) and for the storage systems required to accommodate the rising use of renewable energy on the electricity grid. Energy storage is critical in addressing the variability in electricity generation from renewables and meeting the increased demand for electricity.

Lithium-ion batteries currently dominate due to their high energy density and lower costs and are widely used in EVs, grid applications and portable electronics. In the UK, batteries account for 5.8 GWh of installed energy storage with an additional 44 GWh needed by 2030 to support the transition to Net Zero.[33] Globally, the recent pledge at COP29 aims to deploy 1,500 GW of energy storage by 2030, a sixfold increase from 2022 levels[34], with 85% of this capacity expected to come from lithium-ion batteries.

Current generation lithium-ion batteries are nearing their performance limits, although costs are expected to continue to fall towards 2030 (see Data sheet Figure 5). Next-generation alternatives such as solid-state, lithium-sulphur, sodium-ion and redox flow batteries are emerging to meet higher performance requirements or compete on cost with lithium-ion batteries. Technology readiness levels (TRLs) for these next-generation battery technologies vary by battery chemistry (see Data sheet Table 1).

Solid-state batteries are a promising next-generation technology offering energy density improvements and enhanced safety.[35] Although research is high risk and long term, solid-state batteries have the potential for high commercial returns.

Sodium-ion batteries are emerging as a cost-effective and sustainable alternative to lithium-ion technology. They are particularly suited to applications for grid storage, home energy systems and low-performance EVs due to their cost, safety and ease of handling during transportation.[36]

Lithium-sulphur batteries are useful for lightweight applications such as drones, satellites and short-range aircraft and have the potential for lower material

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[33] Faraday Insight 21 (October 2024), Batteries in Stationary Energy Storage Applications https://www.faraday.ac.uk/insights/insight-21-batteries-in-stationary-energy-storage-applications/

[34] COP29 Global Energy Storage and Grids Pledge https://cop29.az/en/pages/cop29-global-energy-storage-and-grids-pledge

[35] Faraday Insight 5 (February 2020), Solid-State Batteries https://www.faraday.ac.uk/insights/insight-5-solid-state-batteries

[36] Faraday Insight 11 (May 2021), Sodium-ion Batteries https://www.faraday.ac.uk/insights/insight-11-sodium-ion-batteries-inexpensive-and-sustainable-energy-storage/

costs due to the availability of sulphur. However, there are challenges related to manufacturing costs and short cycle life.[37]

Redox-flow batteries could be suited for stationary storage applications to maintain grid stability as renewable energy generation increases.

Metal-air batteries, including zinc-air, could be used for high-density applications such as aerospace and defence purposes although they are in an early development stage. Some metal-air chemistries, such as iron-air, are also being developed as low-cost energy storage technologies.

Future R&D

Advancing battery technologies requires breakthroughs in cost reduction, energy density, power density, thermal management, life extension, recycling and safety, along with strengthening industrial-academic collaboration. Manufacturing efficiency, production improvements and novel cell designs will also play a key role in advancing the technology across different applications. Any performance improvements will need to be tailored to specific applications, such as high energy density and low weight for aerospace and low-cost and longer duration for stationary and grid applications.

Battery costs have declined over the past decade, with average prices falling by around 80% since 2010 (see Data sheet Figure 5). This trend has been the primary driver of improved EV affordability. Economies of scale, advancements in manufacturing processes and the recent readoption of the low-cost lithium iron phosphate (LFP) chemistry have contributed to these reductions. Sodium-ion batteries, using abundant and inexpensive materials, offer potential for further cost reductions while enhancing safety and sustainability (at the cost of cell energy density).

Technology advancements in material efficiency, energy density and manufacturing processes will be needed to further reduce cost and encourage adoption. Low costs are critical for grid stationary storage solutions to remain competitive with alternative technologies and to ensure the economic viability of long-duration storage.[38]

Improving energy density is another advancement needed to help accelerate the adoption of battery technology. Existing lithium-ion batteries such as NMC (nickel manganese cobalt) achieve energy densities of around 250 to 280 Wh/kg while and LFP batteries typically reach around 180 to 200 Wh/kg. Additional increases in energy

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[37] Faraday Insight 8 (May 2020), Lithium-Sulfur Batteries https://www.faraday.ac.uk/insights/insight-8-lithium-sulfur-batteries-lightweight-technology-for-multiple-sectors/

[38] Rho Motion (September 2023). Market and Technology Assessment of Grid-Scale Energy Storage required to Deliver Net Zero https://www.faraday.ac.uk/wp-content/uploads/2023/09/20230908_Rho_Motion_Faraday_Institution_UK_BESS_Report_Final.pdf

density can be achieved by developing silicon and lithium metal anodes and through new innovations in the cathode such as the use of LMFP (lithium manganese iron phosphate) which offers a cell-level energy density of around 240 Wh/kg.[39] In addition, increasing the nickel content in NMC cathodes to create nickel-rich compositions such as NMC9.5.5 can further enhance energy density to 300 Wh/kg, although this may come with trade-offs in thermal stability. Advances in cathodes using alternative structures such as disordered rock salts also promise to enhance capacity and reduce critical mineral dependency.

However, these are incremental enhancements and will not achieve the significant increases in energy density required. Significant breakthroughs will only be achieved through the development and commercialisation of next-generation technologies such as solid-state and lithium-sulphur batteries.

Solid-state batteries promise a step change in energy density with future potential of 400 to 500 Wh/kg, although technical hurdles remain before mass production is feasible. Lithium-sulphur batteries also have a similar practical gravimetric energy density of up to 500 Wh/kg. However, they currently achieve lower energy densities and face challenges such as short cycle lives and the polysulfide shuttle effect. Data sheet Table 2 summarises the energy density and performance metrics that may be achieved by commercially available versions of current and next-generation battery technologies in the next decade or so.

The R&D needed for next-generation battery chemistries focuses on overcoming specific challenges to achieve higher energy densities, improved safety and reduced cost.

- **Solid-state**: Preventing dendrite formation, optimising electrolyte-electrode interfaces and scaling cost-effective manufacturing, as well as prioritising the commercialisation of silicon anode solid-state batteries for near-term applications and the use of lithium metal anodes in the longer-term.
- **Lithium-sulphur**: Addressing the polysulfide shuttle effect, improving the sulphur cathode architecture and enhancing electrolyte formulations to increase efficiency and cycle life.
- **Sodium-ion**: Optimising sodium-based cathodes and hard carbon anodes, stabilising electrolytes and scaling production using existing lithium-ion plants.
- **Redox flow**: Developing cost-effective alternatives to vanadium-based chemistries such as new organic or metal-based electrolytes.

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[39] Faraday Insight 18 (September 2023), Developments in Lithium-Ion Battery Cathodes https://www.faraday.ac.uk/insights/insight-18-developments-in-lithium-ion-battery-cathodes/

- **Metal-air**: Enhancing air cathode catalysts, improving the efficiency of the oxygen reduction reaction and developing solid-state electrolytes to increase stability and cycle life.

Enhancing the safety of lithium-ion batteries is also critical. Although catastrophic failures are rare, they can still occur due to mechanical, thermal or electrical stresses causing a cell to enter thermal runaway, starting fires or the build-up of toxic and flammable gases, which can lead to explosions in very rare cases. Key safety challenges include limited access to specialised testing facilities, gaps in disseminating best practices and insufficient research collaboration on the safety of next-generation batteries. Addressing these through improved testing capabilities, updated protocols and strengthened industry-academic partnerships will reduce safety risks. Advances in battery management systems, safety-focused design and robust testing methodologies will also enhance the reliability of cells and packs.[40]

Technological advancements in recycling are needed to raise recycling rates, lower costs, reduce reliance on imported materials and establish a robust UK lithium-ion battery recycling industry. Current recycling methods, primarily pyrometallurgy and hydrometallurgy, face challenges related to recovery rates, cost efficiency and environmental impact. Research into direct recycling, a process that recovers materials from used batteries without breaking them down completely, could help but requires scale-up and automation. Integrating bioleaching and advanced separation techniques could further optimise material recovery and minimise environmental impact. Finally, designing batteries with recyclability and second-life applications in mind will be essential for reducing costs and minimising environmental impacts.[41]

Wider technology dependencies will also play a crucial role in the development of battery technology. Advanced computer modelling is transforming the development process by reducing the cost and time for developing new batteries and eliminating the reliance on physical prototypes. These methods range from modelling at atomic level to cell and pack design.[42] Machine learning can further accelerate material discovery and improvements in battery management, while quantum computing has the potential to enable breakthroughs in ultra-fast charging. Finally, strengthening the UK's research output, patents and investments will also be critical to improving UK competitiveness in the development and commercialisation of next-generation batteries.

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[40] Faraday Insight 17 (July 2023), Improving the Safety of Lithium-ion Battery Cells Insight 17: Improving the Safety of Lithium-ion Battery Cells - The Faraday Institution

[41] Faraday Insight 20 (July 2024), Developing a UK lithium-ion battery recycling industry Insight 20: Developing a UK lithium-ion battery recycling industry - The Faraday Institution

[42] Faraday Insight 15 (December 2022), The Value of Modelling for Battery Development and Use https://www.faraday.ac.uk/insights/insight-15-the-value-of-modelling-for-battery-development-and-use/

Challenges

Hurdles in the commercialisation of battery technology include structural, financial and policy barriers that impede the commercialisation of research, for example insufficient access to research infrastructure, supply chain constraints, workforce development and regulatory instability.

Although the UK has strong academic research capabilities in battery technologies, translating these advancements into commercial applications remains challenging. The limited availability of suitable facilities and resources for scaling up research and fragmented coordination among stakeholders in particular limit the scalability of innovations. High capital costs for equipment combined with short-term funding cycles also discourage long-term R&D investments.

The absence of a comprehensive domestic battery supply chain constrains the UK's ability to capitalise on the growing demand. While the UK has launched a battery strategy[43] that addresses supply chain weaknesses, it will require significant strengthening and sustained commitment to ensure its long-term effectiveness. Dependence on imports for critical materials such as lithium, cobalt and nickel, subjects the sector to supply chain shocks. The lack of domestic capabilities for material separation, processing and component manufacturing further escalates costs and logistical complexities. Strengthening the UK's supply chain is vital to reduce reliance on dominant suppliers such as China.[44] While global resources of critical materials such as lithium, cobalt and nickel are sufficient to meet growing demand, the UK's ability to compete in a tightening market emphasises the need for stronger domestic supply chains.[45]

Battery development requires substantial investment, often exceeding £100 million through an opportunity's lifecycle. Start-ups and SMEs struggle to secure funding for high-risk, capital-intensive projects. The limited presence of established battery manufacturers in the UK complicates access to industrial funding, deterring investors. Rapid technological advancements and uncertainty in market adoption rates, particularly for EVs, add financial risks to investments.

The battery sector faces acute skills shortages, with high global demand for engineers and scientists experienced in battery technologies. The emergence of gigafactories and advanced battery manufacturing amplifies the need for a skilled

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[43] Department for Business and Trade (2022).UK Battery Strategy https://www.gov.uk/government/publications/uk-battery-strategy

[44] HM Government (2022). Resilience for the Future: The UK's Critical Minerals Strategy https://www.gov.uk/government/publications/uk-critical-mineral-strategy

[45] Faraday Insight 6: (September 2022). Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century https://www.faraday.ac.uk/insights/insight-6-lithium-cobalt-and-nickel-the-gold-rush-of-the-21st-century/

workforce. Although initiatives such as the Electrification Skills Network, Electric Revolution Skills Hub, National Battery Training and Skills Academy and battery technician apprenticeships aim to address these gaps, the UK lags in workforce readiness compared to competitors in Europe, Asia and the US. Enhancing skills through a nationwide development strategy is essential to meet the sector's growing demands and maintain competitiveness.

Frequent regulatory changes and inconsistent policy priorities, particularly around incentives for EVs, hinder long-term planning and investment. Policy measures could include strengthening extended producer responsibility and implementing eco-design standards to foster innovation and encourage market participation. Addressing intellectual property complexities and establishing clear guidelines for critical mineral sourcing, battery labelling and end-of-life management are also important to support a circular battery value chain. In addition, streamlining permitting processes for battery manufacturing and recycling facilities and ensuring timely grid connectivity are essential to enable investment and infrastructure development.

UK strengths

The UK is well-positioned to capture a share of the global demand for batteries, projected to reach as much as 8 TWh by 2050[46]. With over 83 startups raising more than US$ 2.4 billion in venture capital investment since 2018 and now valued at over US$ 3 billion[47], the UK's role in the global EV battery sector is gaining momentum.

The UK's efforts in establishing new gigafactories is also beginning to materialise, with substantial investments taking place across the UK. Agratas is building a 40 GWh plant in Somerset, AESC is expanding in Sunderland, and plans are underway near Coventry. However, to meet the projected demand of 110 GWh by 2030 requires further expansion, with at least six gigafactories operational by then (see Data sheet Figure 6).[48] Further ahead, 200 GWh of supply equivalent to ten gigafactories will be needed in the UK by 2040 to meet battery demand across private cars, commercial vehicles, HGVs, buses, micromobility and grid storage.

The UK is recognised for expertise in next-generation batteries, including solid-state, sodium-ion and lithium-sulphur technologies. Given that commercial-scale manufacturing of next-generation batteries such as solid-state and lithium-sulphur is still emerging, the UK has an opportunity to leverage its research strengths to create economic value and high-quality jobs in battery manufacturing.

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[46] BNEF (June 2024). Electric Vehicle Outlook 2024 https://about.bnef.com/electric-vehicle-outlook/

[47] Dealroom.co. Electric vehicle battery tech in the UK 2024 https://dealroom.co/guides/fbc-uk-battery-study-2024

[48] Faraday Institution (September 2024). UK electric vehicle and battery production potential to 2040 https://www.faraday.ac.uk/news-ev-battery-prod-2040-update-sept2024/

Government initiatives such as the Faraday Battery Challenge, UK Battery Industrialisation Centre (UKBIC) and the Faraday Institution align academic research with industrial needs, fostering collaboration across sectors. Commercialisation efforts are further reinforced through organisations such as the Advanced Propulsion Centre, which is focused on accelerating the development and industrialisation of low-carbon vehicle technologies including batteries. These initiatives enhance the UK's capacity to commercialise and manufacture advanced battery technologies, addressing demand in automotive, grid storage and aerospace sectors.

Academic institutions are key to this success. Leading universities, including Oxford, Cambridge, UCL, Imperial, Warwick, Birmingham and St Andrews, have contributed to global battery research. The Faraday Institution has convened 10 major projects involving 25 universities and over 140 industrial partners, strengthening the UK's innovation ecosystem (see Data sheet Figure 7).

The UK also excels in high-power applications, supported by motorsport expertise. Companies such as McLaren and Fortescue Zero lead in high-performance systems, while Faradion advances sodium-ion technologies, reinforcing the UK's role in energy storage innovation.

The UK has world-leading expertise in early-stage R&D and innovative methods for treating end-of-life batteries. Academic institutions, start-ups and spinouts are focused on recovering harder-to-extract or less lucrative materials within EV batteries, improving recycling efficiency and raising recovery rates. In addition, companies such as Green Lithium, Tees Valley Lithium and Glencore are developing refinement capabilities with a particular focus on lithium.

International partnerships enhance the UK's capabilities in battery innovation. The Faraday Institution collaborates with a number of US Department of Energy's national laboratories on reducing critical mineral use and recycling. Similar partnerships with Japan and the Lithium Triangle nations Chile, Argentina and Bolivia aim to secure resources and strengthen global research ties. Re-engaging with the European battery research programme through Horizon Europe could also improve the UK's competitiveness in the global battery sector.

Potential

Advancing battery technologies could transform the UK's decarbonisation journey, driving progress toward Net Zero and helping to deliver the 200 GWh of battery supply needed in the UK by 2040 (see also Data sheet Figures 8, 9).

Lithium-ion technology is expected to meet near-term demand and will continue to play a central role in providing stability to the grid and in the transport sector. However, new battery technologies are needed for new applications such as long duration energy storage, enhanced grid resilience and to prevent an over reliance on lithium-ion technology.

Some of the advancements that could be made include:

- Improvements to lithium-ion and solid-state batteries, which could accelerate EV adoption by increasing the available range of cars, while addressing issues around manufacturing challenges could help further reduce the costs to make EV's a more affordable option.
- Development of next-generation chemistries such as lithium-sulphur and metal-air batteries, which could enable lightweight and high-capacity solutions for aerospace, drones and off-road vehicles.
- Innovations in sodium-ion batteries, which could offer a low-cost alternative to lithium-ion, particularly for applications such as stationary storage and in competition with LFP or LMFP for affordable battery EVs.
- Exploration of other low-cost battery chemistries, such as redox-flow and iron-air batteries, which could be used to deliver the long duration energy storage solutions critical for energy security.

These advancements require substantial, long-term and stable R&D investment, but to meet the UK's projected demand for 200 GWh of battery capacity by 2040 and to support the decarbonisation of transport and energy sectors, breakthroughs in energy storage technologies will be needed. Scaling up battery energy storage will also play a crucial role in enhancing grid resilience and securing a stable and self-sufficient energy system for the UK.

Glossary

Term	**Description**
Energy density	Amount of energy stored in a battery per unit of weight or volume
Practical energy density	Energy density levels that are likely to be reached commercially in the future
Gravimetric energy density	The energy a battery can store in weight terms, that is Watt hours per kilogram (Wh/kg)
Volumetric energy density	The nominal battery energy per unit volume, that is Watt hours per litre (Wh/l)
Roundtrip efficiency	How much energy is lost during a full charge-discharge cycle which will be different according to battery technology
Polysulfide shuttle effect	Polysulfides formed during cell operation shuttle between electrodes, causing a loss of active sulphur from the cathode
Bioleaching	Utilises bacteria or fungi to produce inorganic or organic acids that can be used for leaching, a process to recover materials.
Gigafactory	A large-scale manufacturing facility for producing battery cells, modules and packs.

Contributors

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Data sheet

Table 1: Technology readiness level by battery chemistry

Battery	TRL	Potential and challenges
Lithium-ion	TRL 9	Mature and widely deployed
Solid-state	TRL 4 – 6	High energy density but costly and early-stage
Sodium-ion	TRL 7 – 9	Cost-effective but needs testing for commercial use
Lithium-sulphur	TRL 4 – 6	High energy density but unstable cycle life
Redox flow	TRL 7 – 9	Scalable, long-life but expensive materials
Metal-air batteries	TRL 1 – 3	High energy but poor roundtrip efficiency

Table 2: Practical cell level energy density and performance metrics by battery technology

Battery chemistry		Energy density	
		Gravimetric (Wh/kg)	Volumetric (Wh/L)
Current	Lithium (current)	280	700
Future potential	Lithium-metal anodes	450	1,000
	Silicon anodes	450	950
	Lithium-sulphur	500	700
	Solid state sulfide	500	1,200

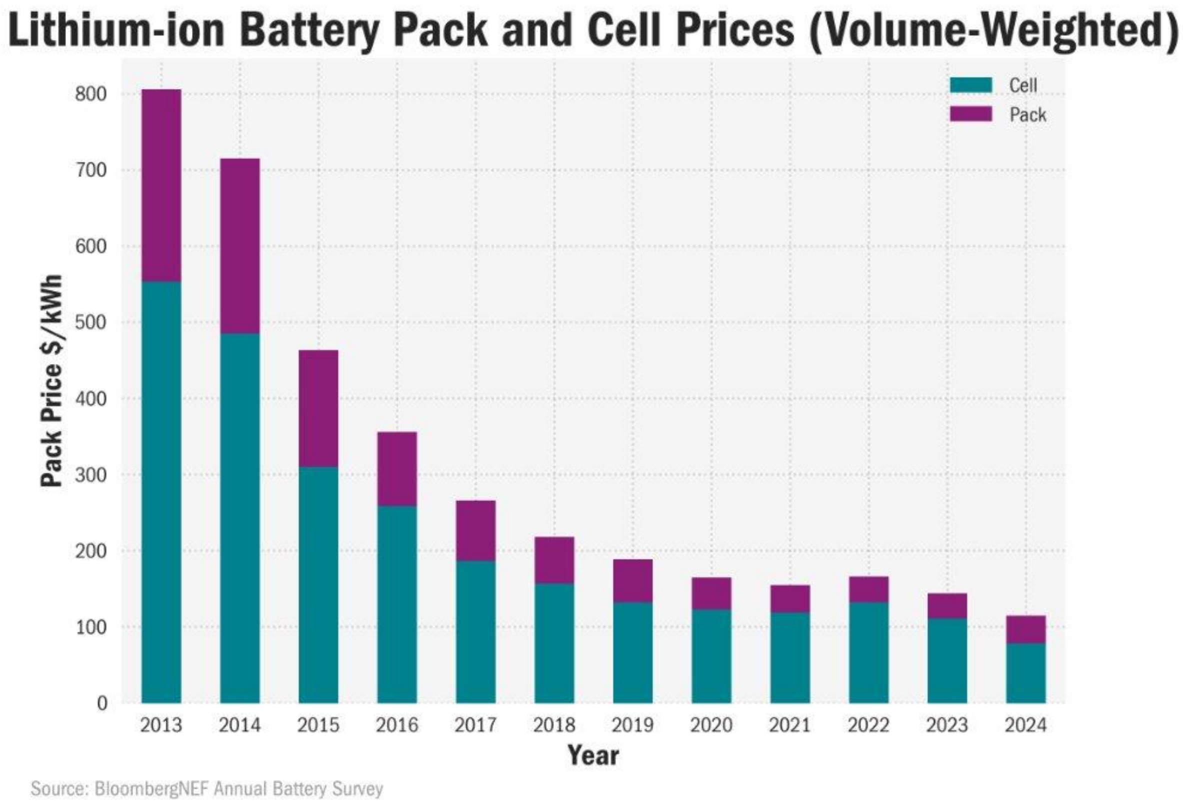


Figure 5 Price of Li-ion battery packs per year. Data source: https://www.iea.org/data-and-statistics/charts/price-of-selected-battery-materials-and-lithium-ion-batteries-2015-2023

European Gigafactories

UK
① AESC Sunderland 1.8GWh 2012
② AESC Sunderland 15.8GWh 2025
③ Agratas Somerset 40.0GWh 2026

Norway
④ Morrow Batteries Agder 43.0GWh 2024
⑤ Beyonder Haugaland 10.0GWh 2025
⑥ Elinor Trondheim 40.0GWh 2026

Sweden
⑦ Northvolt Skellefteå 60.0GWh 2021
⑧ NOVO Gothenburg 50.0GWh 2025

Germany
⑨ CATL Erfurt 14.0GWh 2022
⑩ Leclanché Willstätt 2.5GWh 2021
⑪ Tesla Berlin 100.0GWh 2022
⑫ PowerCo Salzgitter 40.0GWh 2025
⑬ SVOLT Überherrn, Saarland 24.0GWh 2024
⑭ Automotive Cell Company Kaiserslautern 40.0GWh 2025

France
⑮ Northvolt Heide 60.0GWh 2026
⑯ Automotive Cell Company Nersac 2.0GWh 2022
⑰ Automotive Cell Company Douvrin 40.0GWh 2024
⑱ Verkor Dunkirk 50.0GWh 2025
⑲ Envision Douai 30.0GWh 2025
⑳ Prologium Dunkirk 48.0GWh 2026

Czech Republic
㉑ Magna Energy Storage Horní Suchá 50.0GWh 2025

Slovakia
㉒ InoBat Bratislava 20.0GWh 2027

Serbia
㉓ InoBat Cuprija 32.0GWh 2027
㉔ ElevenEs Subotica 16.0GWh 2024

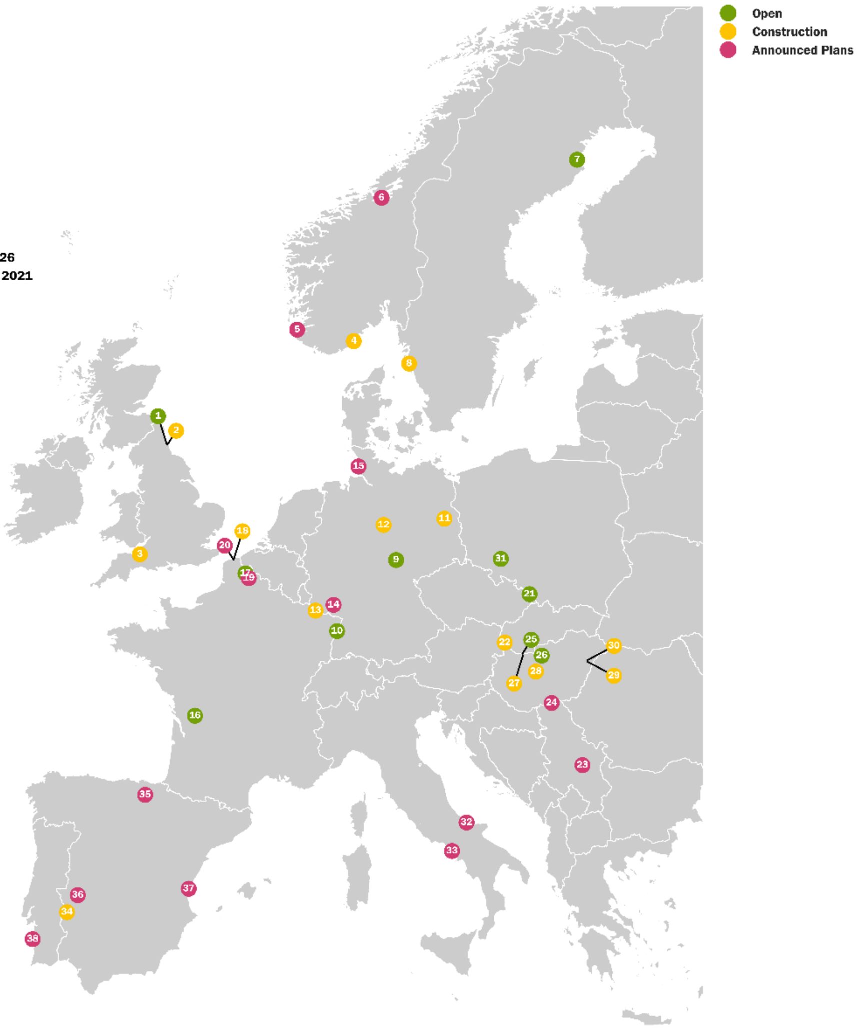
Hungary
㉕ SK Innovation Komárom 1 7.5GWh 2020
㉖ Samsung Göd 40.0GWh 2018
㉗ SK Innovation Komáron 2 9.8GWh 2024
㉘ SK Innovation Ivancsa 30.0GWh 2024
㉙ CATL Debrecen 100.0GWh 2025
㉚ EVE Energy Debrecen 28.0GWh 2026

Poland
㉛ LG Energy Solutions Wroclaw 115.0GWh 2018

Italy
㉜ Automotive Cell Company Termoli 40.0GWh 2026
㉝ FAAM Research Centre Teverola 1 & 2 7.8GWh 2021

Spain
㉞ Phi4Tech Badajoz 18.0GWh 2023
㉟ BasqueVolt Euskadi 10.0GWh 2027
㊱ AESC Cacares 50.0GWh 2025
㊲ Volkswagen Sagunto, Valencia 40.0GWh 2026

Portugal
㊳ CALB Sines 45.0GWh 2025



Source: Faraday Institution, IOP

Figure 6 Map of European gigafactories. Data source: https://www.faraday.ac.uk/wp-content/uploads/2024/09/Gigafactory-Report_2024_final_17Sept2024.pdf

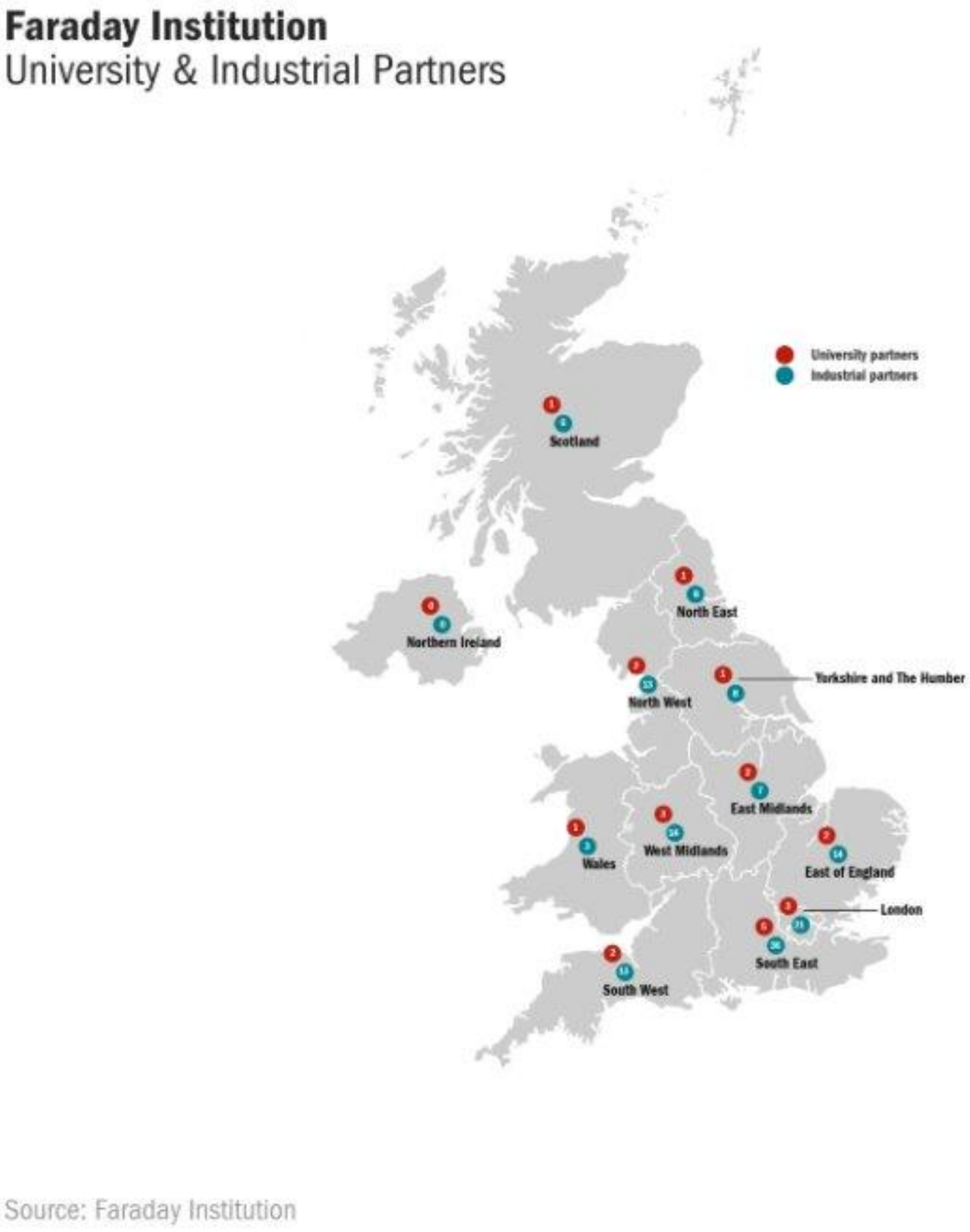


Figure 7 UK map of Faraday Institution partners. Data source: https://www.faraday.ac.uk/commercialisation/industry-partners/

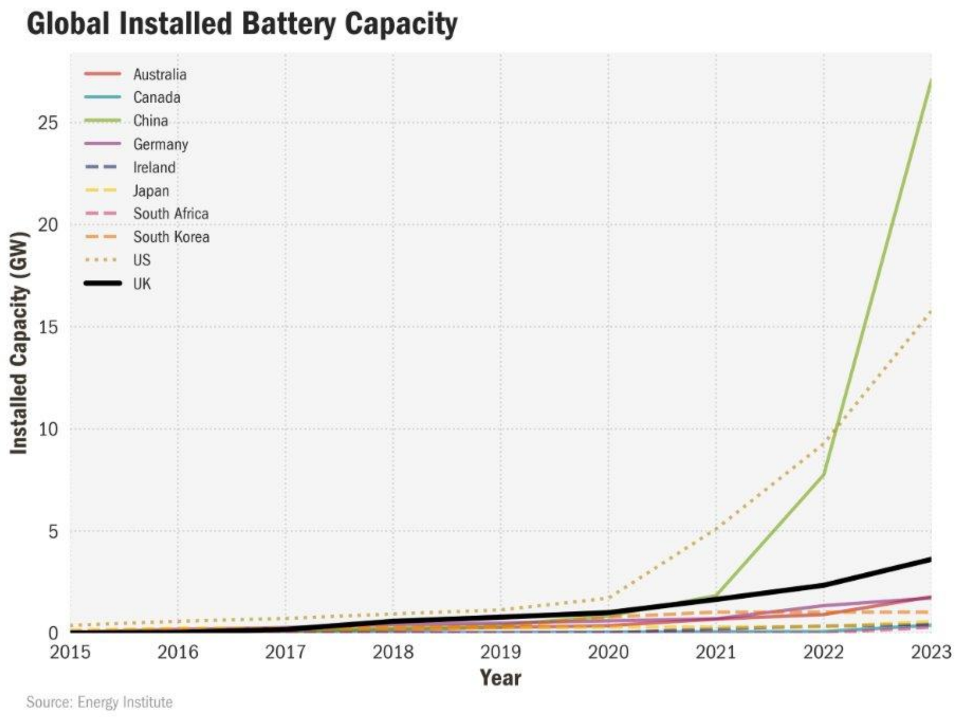


Figure 8 Global installed battery capacity per country. Data source: https://www.energyinst.org/statistical-review

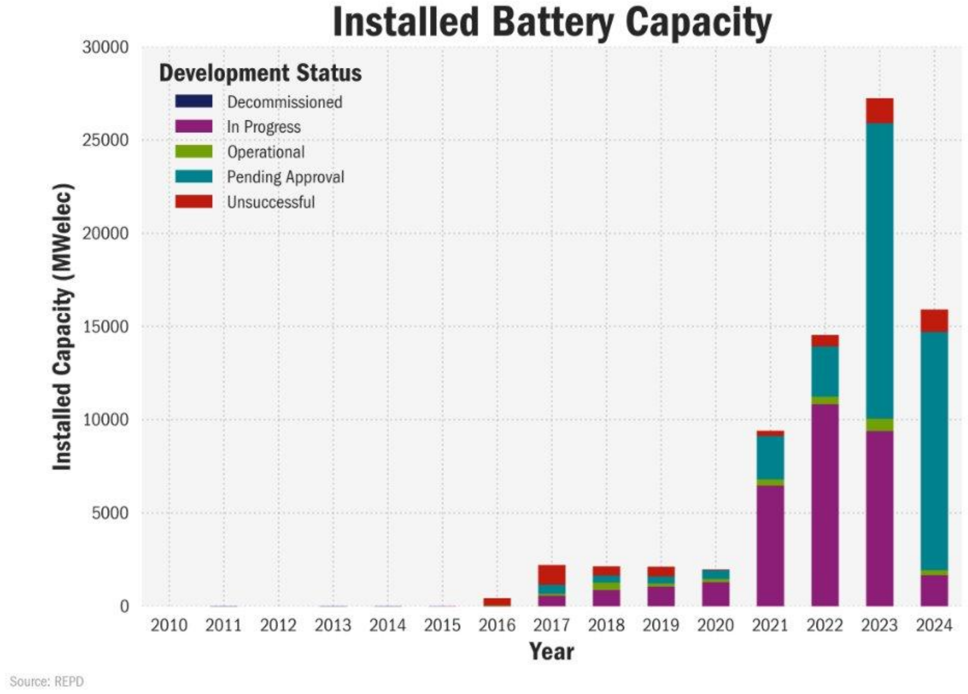


Figure 9 UK installed battery capacity. Data source: https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract

Energy transmission: High-temperature superconductors

Summary

State of the art

- High-temperature superconductors (HTS) in electricity transmission have the potential to dramatically reduce energy losses. HTS technology therefore promises reduced energy losses, enhanced grid capacity, and a more sustainable energy infrastructure
- HTS materials are often ceramic based, but their brittleness presents challenges in manufacturing and deployment

Challenges

- Reducing cost
- Tackling the material fragility
- Infrastructure integration
- Improved manufacturing

UK strengths

- Integration with renewables, interconnectors, microgrids
- Spill-over advances from fusion

Opportunities

- Initial investment in HTS infrastructure is high, but the long-term savings from decreased energy losses, enhanced grid capacity and stability, leading to a more sustainable energy infrastructure can offset these expenses

State of the art

In conventional power lines, resistance to electrical current causes energy dissipation as heat, leading to transmission losses that account for approximately 5-10% of generated electricity globally. In the UK, where electricity demand is projected to rise significantly due to electrification of transport and heating, these losses translate to approximately 8% which is 25 TWh or 3.75 billions of pounds annually[49,50] (assuming a representative price of £0.15 Per kWh).

In addition, the UK's electricity grid faces significant challenges related to bottlenecks, particularly as renewable energy sources such as offshore wind farms contribute a growing share of power. These bottlenecks occur when the existing transmission infrastructure cannot accommodate the volume of electricity being generated, leading to inefficiencies and increased costs. An example project to mitigate this is Eastern Green Link 2 (EGL2) which will reinforce Britain's electricity network with a 2 GW HVDC electrical 'superhighway' cable link between Peterhead in Aberdeenshire and Drax in North Yorkshire, most of which will run in the North Sea. When complete in 2029, it will carry enough electricity for two million households and save an estimated £1.5 billion annually[51].

Superconductors are materials that exhibit zero electrical resistance and expel magnetic fields when cooled below a critical temperature. Conventional superconductors require extremely low temperatures, typically achievable only with liquid helium cooling, but high-temperature superconductors (HTS), such as yttrium barium copper oxide (YBCO), operate at temperatures above the boiling point of liquid nitrogen (77 K or -196°C), making cooling significantly more practical and cost-effective. See also Data sheet Table 1.

The defining characteristic of HTS materials is their ability to carry enormous current densities without energy dissipation. This arises from the formation of Cooper pairs, where electrons bind together to move through the material without scattering. Unlike conventional superconductors, HTS exhibit complex behaviours involving d-wave pairing symmetries and strong electron correlations, making them a subject of ongoing research. The main HTS materials are YBCO and the family of materials known as rare earth barium cuprate (REBCO) superconductors, bismuth strontium calcium copper oxides (BSCCO) and magnesium diboride (MgB_2), but new materials are being

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[49] Electricity lost in transmission in the United Kingdom (UK) in selected years from 1970 to 2022, https://www.statista.com/statistics/550583/electricity-losses-in-transmission-uk/

[50] Electric power transmission and distribution losses United Kingdom https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=GB

[51] Proposed Anglo-Scottish electricity superhighway is first to clear final fast-track funding hurdle (August 2024) https://www.ofgem.gov.uk/press-release/proposed-anglo-scottish-electricity-superhighway-first-clear-final-fast-track-funding-hurdle

discovered, such as iron pnictides and chalcogenides, however these cannot yet be used in practical applications.

HTS materials[52] are often ceramic based, composed of copper oxide planes that play a critical role in their superconducting properties. The layered structure of these materials facilitates high conductivity, but their brittleness presents challenges in manufacturing and deployment.

One of the advantages of HTS in electricity transmission is their potential to dramatically reduce energy losses. HTS cables, with their zero-resistance property, eliminate this loss entirely when operating in their superconducting state. HTS technology therefore promises reduced energy losses, enhanced grid capacity, and a more sustainable energy infrastructure. It would be impractical to replace the entire grid with superconducting cables but said cables could increase capacity in crucial pinch points and the savings made due to the reduction in losses would help to offset the cost of the upgrades.

Current applications and demonstrations

Several successful demonstrations of HTS technology highlight its potential for transforming electricity transmission:

- **AmpaCity Project (Germany):** This initiative replaced a 1 km-long copper cable with an HTS cable in Essen, reducing energy losses and freeing up space in the urban grid. The project demonstrated the feasibility of HTS in real-world conditions[53]. Follow up projects include HYDRA in the US and Ishikara in Japan. Nexans who were involved in Ampacity have strengthened the grid in Montparnasse and Chicago[54].

- **Superconducting Cables in New York:** A project in Long Island, New York, deployed HTS cables to enhance grid reliability and prevent power outages. These cables effectively transported large amounts of power through a narrow corridor, showcasing their urban applicability. Known as the Holbrrok project this was commissioned in 2008 and is still in operation.

- **Fault Current Limiters (FCL):** Utilities worldwide are testing HTS fault current limiters to protect grids from power surges. These devices have proven effective in enhancing grid resilience and reducing maintenance costs. There have been

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[52] Coombs, T.A., Wang, Q., Shah, A. *et al.* High-temperature superconductors and their large-scale applications. *Nat Rev Electr Eng* **1**, 788–801 (2024). https://doi.org/10.1038/s44287-024-00112-y

[53] World's longest superconductor cable proves successful (October 2014) https://www.imeche.org/news/news-article/world%27s-longest-superconductor-cable-provides-hope-30101401

[54] Superconducting cables: fast transmission and no energy losses, https://www.nexans.com/markets/activities/markets/power-distribution/superconductivity/

many FCL projects a representative list can be found here[55]. FCLs started off protecting AC grids but over the years there has been a move to DC transmission and the technology has been shown to work here too for example the Nan'ao VSC-HVDC transmission system, was put into operation on August 17, 2020 [56].

- **Superconducting Wind Turbines:** Research into HTS-based generators for wind turbines has shown promise in increasing efficiency and reducing the weight of turbine components. This application could revolutionize renewable energy generation. The best illustration of their advantage was ECOSWING where they retrofitted a turbine with an HTS winding[57].

Most applications are at TRL 5-7. Wind turbines have been built and tested in situ (6-7). Cable projects have been built and operated (6-7). HTS for fusion magnets[58], however, is at best at level 3-4. With the exception of the latter, which will still take many years, the TRL of the other technologies could be raised to 8/9 on a shorter timeframe.

Current and future R&D

Current status of HTS for power grids

HTS can advance electricity transmission by enabling efficient, high-capacity power delivery. Different projects demonstrated HTS technology's practical benefits and its progression through various TRLs.

- **SuperRail Project (France):** This initiative involves developing and installing an HTS direct current (DC) cable system to reinforce the power supply of the Montparnasse railway station in Paris. The project's objectives include increasing traffic capacity and reducing CO_2 emissions, showcasing HTS's role in sustainable urban infrastructure[59].
- **IRIS Project (Italy):** The IRIS project aims to build a prototype HTS cable using magnesium di-boride (MgB_2) and establish infrastructure to validate this and other technological solutions. The project focuses on introducing standards essential for the adoption and dissemination of new technologies in society[60].

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[55] Gonçalves Sotelo, G., et al. A review of superconducting fault current limiters compared with other proven technologies, *Superconductivity* **3**, 100018, (2022) https://doi.org/10.1016/j.supcon.2022.100018
[56] Song, M. et al. Design and performance tests of a 160 kV/1.0 kA DC superconducting fault current limiter, *Physica C: Superconductivity and its Applications* **585**, 1353871 (2021) https://doi.org/10.1016/j.physc.2021.135387
[57] EcoSwing https://www.utwente.nl/en/tnw/ems/research/sust/EcoSwing/
[58] Bruzzone, P. *et al* High temperature superconductors for fusion magnets *Nucl. Fusion* **58** 103001 (2018) DOI :10.1088/1741-4326/aad835
[59] SuperRail https://absolut-system.com/projets/our_projects/superrail-superconductivity-in-rail/
[60] IRIS - Innovative Research Infrastructure on applied Superconductivity https://www.mur.gov.it/sites/default/files/2024-03/PSE IR0000003.pdf

- **SuperNode and National Grid Collaboration (UK):** SuperNode, in partnership with National Grid Electricity Transmission (NGET), is developing industry standards for HTS cabling systems. This collaboration aims to revolutionize grid technology by enhancing efficiency and capacity, indicating a commitment to integrating HTS into national energy infrastructure[61].
- **Shenzhen Superconducting Cable (China):** A 400-meter, 10 kV HTS cable supported 10 kA of current, meeting the demanding needs of a high-load urban grid in Shenzhen, China[62].

These projects highlight HTS's practical benefits, including compact infrastructure, high current density, and minimal transmission losses. The implementation of HTS cable technology into transmission typically falls between TRL 6 (Technology Demonstrated in Relevant Environment) and TRL 7 (System Prototype Demonstration in Operational Environment). Advancing HTS technology from its current state at TRL 6-7 to full-scale implementation at TRL 8-9 requires overcoming several critical challenges.

Manufacturing and operation

The manufacturing of HTS cables involves expensive materials such as yttrium barium copper oxide (YBCO) and tackling the complexity of cable fabrication. Producing long, defect-free HTS tapes with uniform coatings and reliable mechanical properties is a demanding process that requires innovative manufacturing techniques. Scaling these processes to industrial levels without compromising quality or performance remains a key hurdle. There are efforts in Europe and the US, but the market leaders tend to be base in the APAC region (China, Korea and Japan)[63].

Additionally, cryogenic cooling systems are integral to HTS operation. These need further development to improve energy efficiency, reduce operational costs, and minimize system size for easier integration into urban and remote settings. The compatibility with existing grid infrastructure also poses a challenge, as HTS systems must seamlessly integrate with legacy HVAC and HVDC systems while adhering to stringent grid standards. Furthermore, the lack of standardized testing and certification protocols for HTS cables complicates their adoption, making it necessary to establish universal benchmarks to ensure reliability and performance.

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[61] SuperNode https://supernode.energy/

[62] China's first self-developed new superconducting cable is put into operation in Shenzhen (June 2022) https://www.yellowrivercloudcable.com/news/EN-4.html

[63] High-Temperature Superconducting Cables Market Size, Industry Share and Forecast 2032, https://www.fortunebusinessinsights.com/industry-reports/high-temperature-superconducting-cables-market-101299

Challenges

Despite the advantages, the widespread adoption of HTS technology faces several challenges:

- **Cost:** The production of HTS materials remains expensive due to complex manufacturing processes, such as the deposition of thin films and the alignment of crystal structures. Cooling systems, though more affordable with liquid nitrogen, still add to the overall cost. Developing cost-effective manufacturing techniques is essential to make HTS-based fusion systems economically viable.
- **Material Fragility:** HTS materials are ceramic-based, which makes them brittle and prone to cracking under mechanical stress. In a high-stress environment, this brittleness can pose a serious risk to the durability and reliability of HTS components. Advanced engineering solutions, such as the development of reinforced composite structures, are needed to enhance the mechanical stability of HTS materials and ensure their long-term performance in demanding conditions.
- **Critical Current and Magnetic Field Limits:** While HTS materials can carry high current densities, their performance degrades in the presence of strong magnetic fields. This limitation necessitates careful design and shielding in certain applications.
- **Infrastructure Integration:** Retrofitting existing grids with HTS technology requires substantial investment and careful planning to ensure compatibility with legacy systems. Retrofitting with HTS components involves extensive modifications to ensure compatibility with legacy systems. Additionally, the cryogenic infrastructure required for HTS systems, though less complex than that for traditional superconductors, still demands careful planning and substantial investment. Addressing these integration challenges is critical to facilitating the widespread adoption of HTS technology.
- **Public Awareness and Acceptance:** As with any new technology, public understanding and support are essential for widespread adoption. Educating stakeholders about the benefits of HTS can help mitigate resistance and foster collaboration.

UK opportunities

The UK is a global leader in offshore wind energy, with ambitious targets for expanding capacity[64]. However, transmitting electricity from wind farms in the North Sea to

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[64] The Statistical Landscape of Wind Farms in the UK (October 2024) https://www.greenmatch.co.uk/green-energy/wind-farm

demand centres in the Midlands and the South is a logistical challenge. HTS cables, with their high-power density and minimal losses, could address this by efficiently transporting large volumes of power over long distances without the need for extensive and invasive new infrastructure. Specifically, HTS technology could address the following:

- **Efficient Long-Distance Transmission:** HTS cables enable low-loss transmission of electricity over long distances, facilitating the integration of remote renewable energy sources into the grid.
- **Compact Infrastructure:** The high-power density of HTS cables allows for the construction of underground transmission lines in densely populated areas, reducing land use conflicts and public opposition.
- **Stabilizing Variable Generation:** HTS-based systems, such as superconducting magnetic energy storage (SMES), provide rapid response energy storage, helping to stabilize fluctuations in renewable generation.

Additionally, HTS technology supports the development of microgrids—localized energy systems that can operate independently of the main grid. HTS cables are particularly well-suited for microgrids—localized energy networks that operate independently or in conjunction with the main grid. By integrating HTS technology, microgrids can efficiently manage variable generation from solar panels and wind turbines, enhance energy storage, and provide reliable power during outages. This is especially relevant for rural areas in the UK, where resilience to extreme weather events is increasingly important.

Deploying **HTS cables in urban areas**, where energy demand is high and land for infrastructure is limited, is particularly advantageous. Their ability to transmit large amounts of power through compact cables reduces the need for extensive overhead lines and hence minimizes the impact on their local environment Veir has plans for cables which carry 5-10 times the power of conventional cables[65]. For example, a single HTS cable can carry the equivalent power of multiple copper or aluminum lines, significantly improving energy density and meaning that the cables take less land. This economic advantage is crucial for utilities seeking sustainable and efficient solutions, especially in the UK's densely populated regions such as London and Manchester.

The UK's reliance on **interconnectors** (currently there are nine with a capacity of 9.8 GW with many more planned) for electricity trade with Europe adds another layer of complexity[66] (see Data sheet Figure 10). HTS technology could improve the efficiency of these cross-border links, ensuring stable and low-loss transmission between countries.

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[65] VEIR https://veir.com/

[66] Ofgem Interconnectors https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/interconnectors

This is particularly important as the UK seeks to balance its grid while integrating variable renewable energy sources.

Distributed generation requires a more flexible and adaptable grid to manage the bidirectional flow of electricity. HTS cables and devices can handle sudden changes in power flows without losses or inefficiencies, ensuring seamless integration of decentralized energy sources.

- **High Current Carrying Capacity:** HTS cables can carry current densities several hundred times greater than conventional conductors, enabling utilities to upgrade transmission capacity without expanding existing rights-of-way.
- **Fault Current Limitation:** HTS fault current limiters are devices that protect grids from power surges by temporarily transitioning to a resistive state during faults. This capability helps prevent damage to equipment and ensures uninterrupted power delivery.
- **Reduced Reactance:** HTS cables exhibit low inductive and capacitive reactance, enabling more efficient power flow and reducing the risk of instability in the grid. This is particularly beneficial for long-distance, high-voltage transmission systems.
- **Improved Reliability:** The integration of HTS technology into existing grids can reduce the occurrence of blackouts and brownouts by providing stable, high-capacity transmission pathways. This reliability is vital for industries and regions where power disruptions can have severe economic and social consequences.

Potential

The adoption of HTS in electricity transmission is driven by ongoing advancements in materials science, engineering, and energy policy. Key developments include:

- **Improved Materials:** Research into new HTS materials with higher critical temperatures and better performance in magnetic fields is ongoing. Materials such as iron-based superconductors and cuprates are showing promise.
- **Cost Reduction:** Scaling up production and improving manufacturing processes will reduce the cost of HTS systems, making them more competitive with traditional technologies.
- **Integration with Smart Grids:** HTS cables and devices can enhance the capabilities of smart grids by enabling efficient, high-capacity transmission and real-time fault management.
- **Hybrid Systems:** Combining HTS with other advanced technologies, such as HVDC (high-voltage direct current) systems, could optimize long-distance power transmission.

- **Global Collaboration:** International initiatives, such as the European Supergrid and Asian renewable energy grids, may drive the adoption of HTS technology on a larger scale.
- **Enhanced Manufacturing Techniques:** Automation and additive manufacturing techniques are being explored to streamline the production of HTS materials and components, potentially lowering costs and increasing scalability.
- **Fusion:** Tokamak Fusion reactors such as ITER and Commonwealth Fusion Systems' SPARC are totally dependent on superconductivity to develop the magnetic fields required for containment of the plasma. Based on low temperature superconductors NbTi and Nb3Sn, ITER has had many setbacks. Of more interest at the time of writing are the projects based on YBCO these have attracted both government and private sector funding. These are at a much smaller scale than ITER. The estimated capital cost of a fusion power plant with 1,000 MW of capacity would range from 2.7 to 9.7 billion dollars[67]. The world leader is currently Commonwealth Fusion, but there are many startups which reflects the considerable interest this technology is generating.
- **Data Centres:** Power consumption of Data Centres already high (Today, data centres account for around 1% of global electricity consumption[68]), is projected to rise six-fold in the next ten years driven by factors such as AI. Incorporating HTS buses in data centres would mitigate this value significantly by reducing power losses.

Although the initial investment in HTS infrastructure is high, the long-term savings from decreased energy losses, enhanced grid capacity and stability, leading to a more sustainable energy infrastructure can offset these expenses.

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[67] Fusion Energy via Magnetic Confinement: An Energy Technology Distillate from the Andlinger Center for Energy and the Environment at Princeton University, Article 4:Economics https://acee.princeton.edu/wp-content/uploads/2016/05/ACEE-Fusion-Distillate.pdf

[68] Data Centres and Data Transmission Networks https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks

Glossary

Term	Description
HVDC	high voltage direct current
HVAC	high voltage alternating current
VSC	voltage source converters
Fault Current Limiters	devices that limit the fault current when a fault occurs in a power transmission network without leading to a complete disconnection
Reactance	the opposition to the flow of current from a circuit element due to its inductance and capacitance

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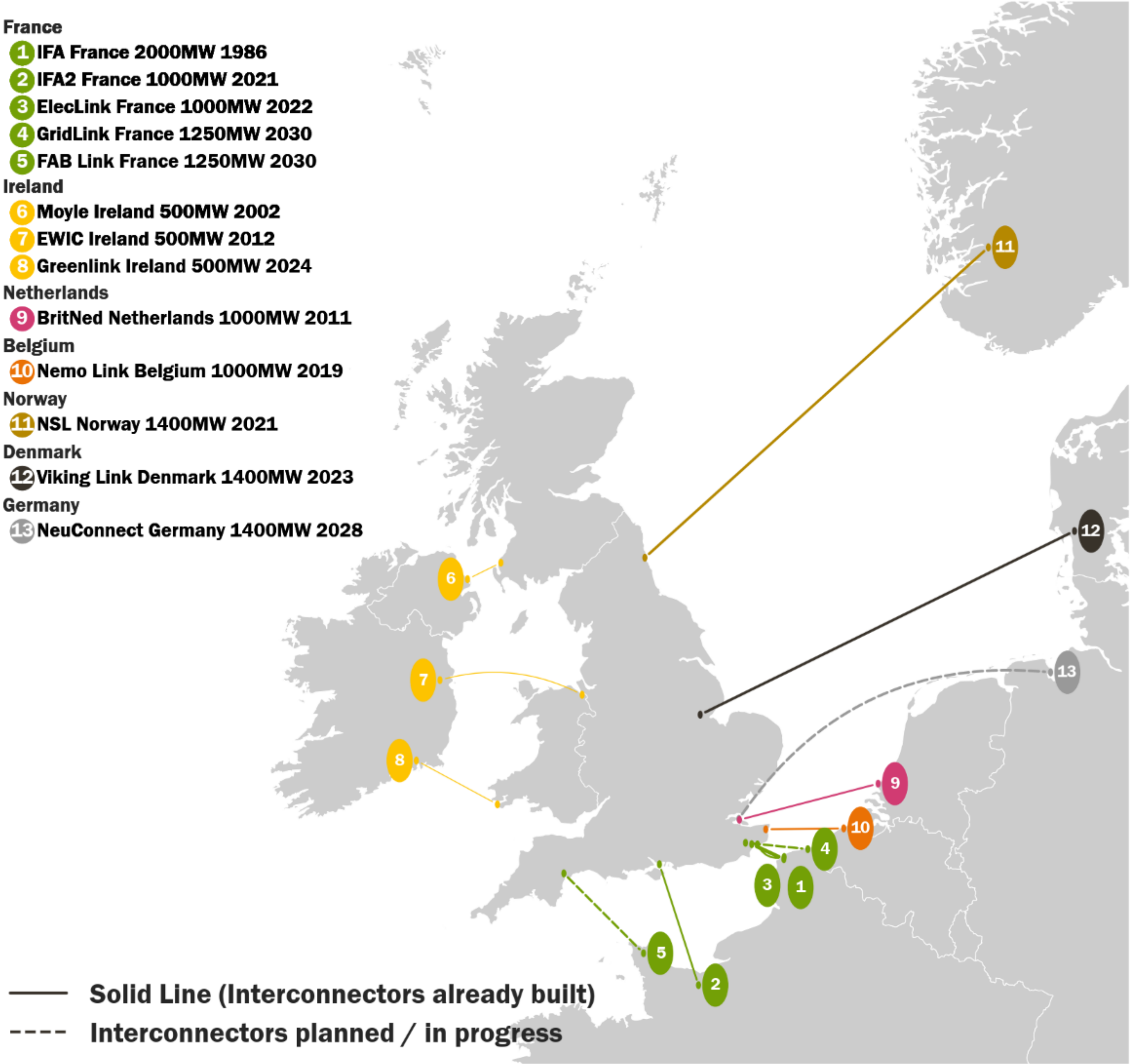
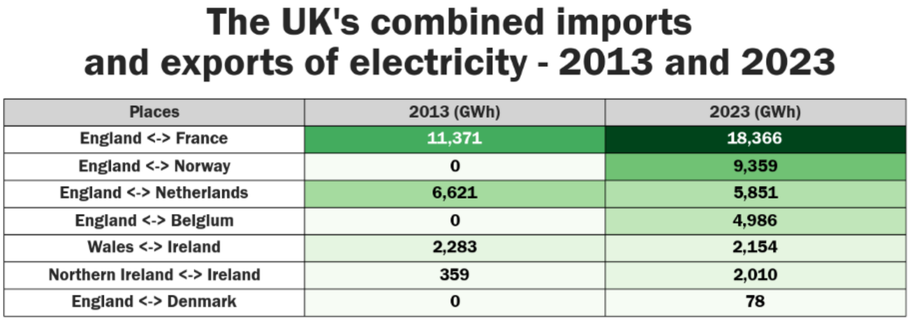
Data sheet

Table 1: Characteristics of HTS materials.

Material	Available form			Operating temperature	Engineering current densities
REBCO	bulk	tape	stacked tapes	<93 K (-180°C)	2×10^9 to 9×10^9 A m^{-2}
BSCCO	bulk	tape	wire	<108 K (-165°C)	2-3 × 10^8 to 7-8 × 10^8 A m^{-2}
MgB_2	bulk	tape	wire	<39 K (-234°C)	3×10^9 to 4×10^9 A m^{-2}





The UK's combined imports and exports of electricity - 2013 and 2023

Places	2013 (GWh)	2023 (GWh)
England <-> France	11,371	18,366
England <-> Norway	0	9,359
England <-> Netherlands	6,621	5,851
England <-> Belgium	0	4,986
Wales <-> Ireland	2,283	2,154
Northern Ireland <-> Ireland	359	2,010
England <-> Denmark	0	78

Sources: DUKES, OfGem, IOP Analysis

Figure 1 UK's interconnectors. Data Source: [*https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/interconnectors*](https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/interconnectors)

Synergies

The UK's push to net-zero emissions is driving a balanced energy mix of renewables, nuclear power, and energy storage. Renewables such as solar and wind energy are variable by nature, whereas nuclear power can supply steady baseload power that is not easily adjusted to meet demand. To bridge the gap between generation and demand, battery energy storage systems are being deployed at scale to store excess electricity and release it when needed while more efficient electricity transmission systems are needed. Coordinating solar (and wind) energy, nuclear power, and battery storage offers a route to enhanced grid stability and reliability.

However, none of the options, variable generation, baseload generation, storage or transmission can solve clean energy needs alone. The combination of all components into an integrated energy system will be more than the sum of its parts and can eliminate need for fossil fuels.

Hybrid energy systems that combine different generation and/or storage technologies are a promising route to decarbonization. Examples include nuclear reactors with renewable sources and energy storage (or fuel production) such as nuclear-renewable hybrid plants can use excess reactor heat or power during low demand periods to produce hydrogen, desalinate water, or charge large batteries. In the UK, Shearwater Energy and NuScale plan[69] to build an SMR-wind plant at Wylfa in Wales which could produce 3 GW of electricity. Other proposed hybrid energy systems designs aim to combine SMRs with solar thermal generation[70] or photovoltaics and battery storage into a single unit. Other examples include the combination of large-scale photovoltaics with hydrogen production[71] and solar generation with long distance transmission[72].

There are several challenges that need to be tackled to achieve an **efficient energy mix using these technologies:**

- Access to critical materials and supply chains. The UK is almost entirely dependent on imports for battery and photovoltaics materials and currently has limited domestic manufacturing capacity. Form a research perspective this challenge motivates the development of new technologies that use different materials and improving the recycling and reuse through better designs.

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[69] https://www.world-nuclear-news.org/Articles/UK-firm-plans-wind-SMR-hybrid-system-with-NuScale

[70] https://world-nuclear-news.org/Articles/Holtec-unveils-hybrid-nuclear-solar-power-plant-de

[71] https://www.offshore-energy.biz/chinas-integrated-solar-power-hydrogen-and-energy-storage-project-connects-to-grid/

[72] Grid integration: Tackling solar connection complexities in the UK and Ireland (February 2024) https://www.solarpowerportal.co.uk/grid-integration-tackling-solar-connection-complexities-in-the-uk-and-ireland/

- R&D. Despite photovoltaics, nuclear power, and battery storage being mature technologies, R&D is needed to further improve technology performance, and performance of integrated systems. Strengthening basic research and common technology R&D (for example modelling and simulation) could help make advances across the board.
- Manufacturing and deployment barriers. Another challenge is scaling manufacturing and deployment. The need for research facilities and facilities for scaling up new technologies has been highlighted for all technologies discussed in this report. Because such facilities require significant investment, infrastructure that serves several technologies could be more effective. An example is AI and high-performance computing infrastructure that can be used to advance the development of new energy materials and nuclear technologies[73].
- System integration and control. Operating a future grid with renewables, nuclear reactors, and distributed battery storage is a complex control problem. Research is ongoing into advanced energy management systems and algorithms to coordinate these assets in real-time. Physics models and physics-based methods can contribute to tackling this challenge.

HTS for transmission is at a lower TRL and is not part of the energy mix, but like photovoltaics, nuclear and batteries it requires basic research (such as understanding the mechanisms of high-temperature superconductivity) and R&D (for example to solve the problem of material fragility) to further improve technology performance. HTS also faces manufacturing and deployment barriers and there is not yet a mature market for this technology. However, the need for HTS in nuclear fusion could contribute to scaling up production and improving manufacturing processes which will reduce the cost.

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[73] https://ccfe.ukaea.uk/ukaea-to-lead-the-creation-of-a-nuclear-robotics-and-ai-cluster-linking-cumbria-and-oxfordshire/

Conclusion

This report provides technology assessments for four technologies in the areas of energy generation, storage and transmission and identifies common challenges. It also considers the overall UK strengths as well as technology-specific and common opportunities. Renewable generation (wind and solar) and nuclear power will be part of the future energy mix and should work together with energy storage systems and an optimised grid, from a physical (decreased losses) and operational perspective. This combination can be achieved by an integrated R&D and deployment approach. There are also aspects where common challenges can be tackled with targeted cross-technology investment.

State of the art

Batteries and photovoltaics are mature technologies that are already commercially available. Rapid reductions in cost and ongoing performance improvements have made them viable solutions for clean electricity supply with increasing potential to decarbonise the electricity sector. Yet they generate only a small fraction of UK power. UK government targets for clean energy generation could be achieved by supporting advances in R&D, technology integration, development of related technologies (such as transmission & distribution and complementary renewable power sources) and addressing cross-technology challenges listed below. However, the UK could further leverage its strengths in tackling these challenges to not only ensure that the climate targets can be met, but also to enable grid resilience and energy security, avoiding overreliance on other countries.

Challenges

- Insufficient R&D funding
- Insufficient access to research facilities and infrastructure
- Skills shortages
- Critical materials and recycling/waste management
- Need for facilities to scale up new technologies

UK strengths

- Strong academic research
- Collaborations and ties to industry
- Good environment for early-stage companies
- International collaborations

Opportunities

- Meeting the climate change targets with photovoltaics, nuclear and batteries requires investment and other interventions, but these can also enable grid resilience and energy security, reducing overreliance on technology from other countries
- There are several common challenges that, if tackled, can ensure an efficient energy mix using these technologies, namely: access to critical materials and supply chains, basic research and R&D to improve technology performance, scaling manufacturing and deployment, system integration and control

Possible interventions

- To address the skills shortages:

Industry partnerships could be leveraged for training technicians and to deliver industry-academia joint PhD programmes.

National facilities would provide training opportunities, for example a nuclear energy test facility would benefit nuclear operators, designers, academics and regulators or a national centre for standards and testing would serve the entire photovoltaics ecosystem.

- To alleviate the dependence on critical materials and improve recycling:

Policy measures could help strengthen the UK's supply chain for critical materials. For example, strengthening extended producer responsibility and introducing mandatory eco-design standards would foster innovation and encourage market participation. Addressing intellectual property complexities and establishing clear guidelines for critical mineral sourcing, battery labelling and end-of-life management would support a circular battery value chain.

Incentivise large-scale recycling and funding applied research into recycling methods would contribute towards the sustainability of both photovoltaics and battery technologies.

- To maximise the benefit of research and scale-up facilities:

Facilities that serve multiple sectors and provide access to users from academia and industry would have greater impact. A previous report[74] emphasized how major national science and technology facilities provide world-leading capabilities for scientific research and technology development, and that the benefit and value of

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[74] IOP Major National Science and Technology Facilities in the UK – report (July 2022) https://www.iop.org/strategy/productivity-programme/major-national-science-technology-facilities

these facilities goes far beyond infrastructure, providing a hub to grow expertise and support industry.

- To strengthen technological independence:

Increase investment into next generation and alternative technologies and materials, as well as support the upscaling of the resulting innovations is required. New technologies could help the UK move away from markets and supply chains dominated by other countries and would ensure that the UK maintains technology leadership in clean energy.

UK nuclear data capability is currently low and highly reliant on other countries. It is important to build sovereign capacity.

In a rapidly changing global context where the need to decarbonize the economy to combat climate change is more urgent than ever, and the need for energy security and access to critical materials and supply chains is becoming more important, the role of R&D is key to meeting the climate targets, developing resilience and boosting the economy. Physics research and innovation are essential to ensure that UK will secure its energy supply with home-grown, clean power.

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