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Solar's rightful place in the sun

A new roadmap for photovoltaics.

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Solar power is in the limelight in the combat against climate change, and for good reason.

Solar photovoltaics (PVs) are now the cheapest form of electricity in many regions across the globe and their role in meeting net-zero targets is increasing.

But while solar panels are now part of the everyday landscape on our rooftops, the technological foundation is seeing a rapid shift.

This innovation drive is critical. To stay within the global warming limit as set by the *Paris Agreement*, solar PV deployment needs to grow nearly tenfold by 2050.

The International Renewable Energy Agency states that global solar capacity must grow from around 0.9TW in 2021 to at least 8.5TW by 2050 to stay on track for net-zero, which is considered a conservative estimate. Other models with higher electrification predict that 80TW of PV by 2050 is needed.

Practically speaking, that means building solar infrastructure at an unprecedented rate – not just in scorching deserts, but in cities, on farms, inside buildings and even in space.

It also means the solar industry must mitigate challenges that go far beyond incremental efficiency gains – from improving end-of-life recyclability of legacy components to developing materials that perform in new environments indoors and in outer space. And how do we reduce the carbon footprint of PV manufacturing? What materials do we depend on, and how abundant are they?

The future demands an overhaul of solar technologies, as well as the systems that support them. Manufacturing must become more sustainable and less capital-intensive. Supply chains must be made more resilient, especially for critical elements like silver, indium and tellurium. Recycling strategies must catch up quickly, as millions of tonnes of PV cells and components approach end-of-life over the next few decades.

It's a daunting to-do list, but not without opportunities and optimism. The learning curve for solar has historically been steep, and PV electricity cost has fallen faster than most predicted.

A new roadmap, led by researchers from across the UK's PV and materials science community, offers a snapshot of where solar technology stands – and where it must develop.

Published in the *Journal of Physics: Energy*, the *Roadmap on established and emerging photovoltaics for sustainable energy conversion* brings together insights from more than 80 researchers, many of them based at leading UK academic institutions.

The objective is to foster innovation for solar materials and devices to achieve climate goals, while navigating the real-world challenges of supply chains, scalability and sustainability.

This latest roadmap builds on work initiated by the Henry Royce Institute (Royce) as a *National Materials Challenge* in 2020, when the UK's PV community came together to define key challenges and opportunities.

Now, the global picture has changed and so have the technologies competing for impact. From next-generation metal-halide perovskite materials to flexible thin films and agrivoltaics, the conversation has widened well beyond crystalline-silicon panels use, which accounted for 98% of all solar cell production worldwide in 2024, according to the German association VDMA.

As the roadmap highlights, today's electricity generation from PVs is often cheaper than wind or fossil fuels, and it continues to drop. The next goal is to scale that affordably while building in sustainable practices and long-term performance. The UK is well placed to contribute to these global challenges, particularly through research into novel materials, advanced metrology and the development of manufacturing processes with low environmental impact (see box-out on PV technologies below).

Changing landscape

While crystalline-silicon panels continue to dominate the market, the solar landscape is increasingly diverse. Emerging materials and device structures are pushing boundaries in efficiency, flexibility and sustainability.

Across all these technologies, the UK has a strong academic research base, demonstrating our diversity of strength and critical mass in this field. See below how the key technologies stack up.

Technology	Status	Strengths	Challenges	UK involvement
Crystalline silicon (c-Si)	Market leader (98% of global photovoltaic (PV) production)	Mature, stable, cost-effective, abundant	Approaching efficiency limits, brittle, energy-intensive manufacturing	Potential for tandem innovations
Cadmium telluride (CdTe)	Most successful thin-film technology	Low-cost production, scalable, low levelised cost of energy	Limited by tellurium supply, voltage bottleneck	UK research on defect passivation and chalcogenide alternatives
Lead-halide perovskites	Rapidly rising, record certified 27.0% efficiency, close to best efficiency for c-Si	Tuneable bandgap, low-cost processing, high-efficiency potential	Stability, toxicity (lead and solvents), scale-up hurdles	Major UK strength, home to leading labs and commercial players like Oxford PV
Perovskite-silicon tandems	Lab record of certified 34.9% efficiency	Combines best of both components, boosts silicon's efficiency ceiling	Needs long-term stability, scalable manufacturing	UK at forefront of industrial development
Organic photovoltaics (OPVs)	Lab record certified >20%, commercial in niche applications (e.g. indoor, building integrated PV), products passing industry stability standard tests	Lightweight, flexible, potentially low-cost, heavy-metal free, abundant materials, lowest CO_2e footprint, ubiquitous use, easy end-of-life treatment	Lower efficiency, stability under real-world conditions than c-Si, scaling up	UK work on improved materials, including non-fullerene acceptors, scaling and novel applications
Antimony chalcogenides (e.g. Sb_2Se_3)	Early-stage thin-film technology	Abundant materials, Cd-free, scalable	Still low efficiency, needs better understanding of defects	UK groups exploring antimony-based materials as alternatives to CdTe
Dye-sensitised solar cells (DSCs)	Suited for indoor and internet-of-things markets	Performs well in low light, tuneable aesthetics	Limited efficiency for outdoor use compared to c-Si	UK active in next-generation DSC research for smart devices

Hot property

The University of Oxford has been central to advancing the science of metal-halide perovskites. Oxford PV is now bringing perovskite-silicon tandem modules to market, while Oxford Physics hosts the national thin-film cluster facility, bridging fundamental research and industrially relevant development for perovskites and organic PV on proven, scalable, vacuum-deposition processes.

PV innovation also continues in other areas. At the Inorganic Chemistry Laboratory in Oxford, researchers are exploring lead-free alternatives and lifecycle sustainability, while Imperial College London continues to steer device engineering and computational design.

Swansea University's SPECIFIC Innovation and Knowledge Centre has carved out a niche in printable, large-area, solar modules – a vital leap towards low-cost, scalable infrastructure. Meanwhile, researchers at the Universities of Liverpool and Loughborough are developing thin-film technologies such as cadmium telluride (CdTe) and antimony chalcogenides, promising efficient devices.

Advanced materials characterisation is another major UK strength. The National Physical Laboratory (NPL), which collaborates closely with Royce, plays a key role in developing standardised metrology techniques, crucial for ensuring new PV technologies perform reliably over time. UCL and Royce contribute to state-of-the-art imaging and diagnostics, while groups in York, Manchester and Durham work on modelling defects and degradation pathways.

The roadmap also shines a light on new frontiers for PVs, where UK researchers are again at the cutting edge. Teams at Newcastle University are developing indoor photovoltaics tailored for powering Internet of Things (IoT) devices, where traditional silicon cells fall short.

At the University of Surrey and Surrey Space Centre, solar cells are being engineered for space – where radiation, weight and longevity all pose unique challenges.

What connects all this work is a focus on solving real-world issues and ensuring stability, recyclability, scalability and environmental impact. As the PV field evolves, UK institutions continue to play a pivotal role in ensuring the next generation of solar technology is genuinely fit for purpose.

Beyond the grid

The solar revolution is also making progress away from rooftops and solar farms. Photovoltaics are finding their way into places unheard of a decade ago.

Indoor photovoltaics are one of the most exciting of these emerging technologies. With the IoT market expected to surpass 25 billion devices globally, there’s a growing demand for self-powered sensors and systems that don’t rely on batteries.

Conventional silicon panels struggle under artificial lighting, but new materials, particularly organic photovoltaics (OPVs), dye-sensitised solar cells (DSCs), lead-halide perovskites and chalcogenide materials, perform surprisingly well in low light.

Researchers at Universities in Newcastle, Oxford and Swansea are helping to tailor these technologies for indoor use, offering a more sustainable route to powering smart homes, health monitors and environmental sensors.

Meanwhile, agrivoltaics offer a viable solution to the long-standing challenge between food and energy needs. By installing semi-transparent or elevated solar panels over farmland, it’s possible to harvest sunlight for both crops and electricity. Agrivoltaics are gaining traction globally, and the roadmap identifies it as an area where materials innovations – like lightweight, flexible PV modules – will be critical.

UK institutions and PV start-ups are already investigating how novel PV materials might be optimised for these complex environments, where temperature, water retention and light filtering all interact.

On the other hand, the space sector is providing a very different kind of test bed. Satellites and high-altitude platforms demand PV technologies that are lightweight, radiation-resistant and highly efficient.

Perovskites and III-V materials (i.e. a compound containing group three and five elements in a semiconductor) are promising contenders, and researchers at the Universities of Surrey, Glasgow and King's College London are exploring how to adapt next-generation PVs for conditions in space.

These novel applications offer test cases for emerging materials, new deployment models and entirely different performance criteria. In some cases, such as indoor and IoT, they could become the main market for certain PV technologies.

Did you know?

From fundamental materials discovery to commercial-scale deployment strategies, UK universities and research technology organisations are making a global impact in photovoltaics (PV).

Some key companies working in PV manufacturing include Oxford PV, Polysolar, TerraChange Solar and Lightricity Ltd.

The NSG Group is also a major supplier of transparent conducting electrodes to US-based First Solar, which is the world's largest manufacturer of cadmium telluride solar cells.

A bumpy road

Photovoltaics also face a multitude of challenges. The roadmap highlights how the future of PVs will depend not just on pushing efficiencies beyond current limits, but on making solar technologies better, cheaper, cleaner and built to last.

A key challenge is stability. High lab-scale efficiencies are impressive, but long-term stability under real-world conditions is essential if emerging technologies like perovskites are to be commercially viable. Silicon panels typically carry 25-year warranties that newer materials must aim to match or exceed.

Developing accelerated testing protocols that accurately mimic long-term degradation is a key area of ongoing research, and one where the UK is making significant contributions.

Materials availability and supply chain resilience are also an issue. Silicon may be plentiful, but many high-performance PV technologies still rely on materials with geopolitical or economic vulnerabilities, like silver, indium, tellurium and gallium.

The roadmap stresses the importance of finding alternatives or reducing usage through smarter design and manufacturing. This includes a growing interest in earth-abundant materials like chalcogenides and organic materials.

There is also the question of circularity. As PV deployment accelerates, so too will the volume of solar panels reaching end-of-life. *A Nature Physics* paper titled *Unfounded concerns about photovoltaic module toxicity and waste are slowing decarbonization* suggests global solar waste could reach 160Mt by 2050.

So, module recycling and broader thinking about the environmental impact of manufacturing are essential considerations. UK researchers are developing recycling strategies and Life Cycle Assessments that aim to minimise PVs' environmental footprint.

Toxicity is another concern. While the actual volume of lead in halide perovskites is relatively small, public perception and regulatory constraints could limit deployment unless robust mitigation measures are in place.

Recent research into encapsulation, lead-binding additives and safer formulations shows that the issue is being taken seriously. This is an area that will require careful stewardship as perovskite technologies scale up and enter the market.

Perhaps most fundamentally, the solar industry must strike a balance between performance and economies of scale. It's one thing to make a groundbreaking device in the lab, it's another to produce thousands of square metres of modules cost-effectively, using scalable, sustainable processes. The roadmap therefore shows the need for deep collaboration between materials scientists, engineers and industry to foster effective scale-up.

Looking up

From this roadmap, the message is crystal clear. Materials science, particularly its community and the innovation it brings, is essential to driving the success of solar technology.

However, the future of PVs is a systems challenge, one that spans engineering, chemistry, physics, data science, logistics, geography and policy. That also means there are opportunities for innovation everywhere.

The UK's PV community, for all its diversity and collaborative nature, is exceptionally well-placed to lead on many of the challenges outlined here.

The roadmap shows there's no single solution, with a diverse range of markets and opportunities. But there is certainly a path to making innovation in PVs a shining success story for materials science in years to come.

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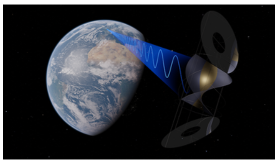

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