MATERIALS FOR THE ENERGY TRANSITION

MATERIALS FOR PHOTOVOLTAIC SYSTEMS

This publication forms part of the 'Materials for the Energy Transition' series. The Henry Royce Institute in collaboration with the Institute of Physics and the Institute for Manufacturing have convened the academic and industrial materials research communities to explore opportunities for materials to support the UK's net-zero by 2050 target.

HENRY ROYCE INSTITUTE

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MATERIALS FOR THE ENERGY TRANSITION ROADMAP:

MATERIALS FOR PHOTOVOLTAIC SYSTEMS

SEPTEMBER 2020

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INTRODUCTION

The Challenge: Materials for the Energy Transition

Following release of the Committee on Climate Change (CCC) 2019 Report[1], the UK is committed to a new greenhouse gas emissions target: net-zero emissions by 2050.

The Executive Summary of the **2019 Committee on Climate Change Report** states:

> ***"Delivery must progress with far greater urgency.***
>
> - ***2040 is too late for the phase-out of petrol and diesel cars and vans, and current plans for delivering this are too vague.***
> - ***Over ten years after the Climate Change Act was passed, there is still no serious plan for decarbonising UK heating systems and no large-scale trials have begun for either heat pumps or hydrogen.***
> - ***Carbon capture (usage) and storage, which is crucial to the delivery of zero GHG emissions and strategically important to the UK economy, is yet to get started. While global progress has also been slow, there are now 43 large-scale projects operating or under development around the world, but none in the UK.***
> - ***However, falling costs for key technologies mean that the future will be different from the past: renewable power (e.g. solar, wind) is now as cheap as or cheaper than fossil fuels in most parts of the world."***

In response, the Henry Royce Institute (the Royce), in collaboration with the Institute of Physics (IOP), has engaged with academic and industrial materials research communities to explore solutions to the grand challenge of **"Materials for the Energy Transition"**. Through roadmapping workshops and associated community-led activities, technologies were identified where materials research can make a significant impact on greenhouse gas emissions.

The key drivers for this work have been (1) the pathways to net-zero emissions suggested in the CCC report, and (2) Royce-supported community workshops undertaken in 2019 to identify areas where investment in UK materials science can generate impact and contribute to the UK's energy transition. These included the "Atoms to Devices" workshop in Leeds (May 2019); the "Operando and In Situ Characterisation of Energy Materials" workshop at the Diamond Light Source in Harwell (July 2019); and, the "Multi-Modal Characterisation of Energy Materials" workshop in Cambridge (November 2019).

As a consequence, the following four areas were identified where materials science is critical to enabling a step-change in greenhouse gas reduction:

1. Materials for photovoltaic systems
2. Materials for low-carbon methods of hydrogen generation
3. Materials for decarbonisation of heating and cooling
    I. Thermoelectric energy conversion materials
    II. Caloric energy conversion materials
4. Materials for low loss electronics

[1] Committee on Climate Change Report: Net-Zero, January 2019, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Materials Roadmaps

In 2020, the Royce together with the respective research communities explored the various materials challenges, targets, and timescales required to support the achievement of net-zero greenhouse emissions by 2050 of the four research areas outlined above. The CCC report and the related materials community engagement emphasised that these four areas are components of a broader ecosystem of materials technologies which together contribute to the UK's goals to deliver net zero by 2050. These roadmaps form the basis for bringing scientific research communities, industry and government together to address immediate and long-term requirements for the development of a suite of energy materials to replace fossil fuel-based energy technologies. The Royce collaborated with the Institute of Physics (IOP) to set out the programme of work and ensure community-wide feedback and engagement. Skills and expertise from the Institute for Manufacturing (IfM) were commissioned to ensure a robust roadmapping methodology, throughout the series of online roadmapping workshops, and to support community discussions.

Roadmap Objectives and Methodology

The main objectives for the five materials roadmaps at the outset were as follows:

- To understand the current state-of-art for each topic
- To define the most significant technical challenges for each area that are providing barriers to impact on net zero targets
- To define the anticipated future challenges for each area in contributing to net zero targets
- To identify solutions to these challenges that can make step-changes in delivery of technologies to contribute to net zero targets
- To identify the desired performance targets of such solutions

The methodology adopted was based on wide-ranging engagement with research communities to define the roadmap objectives and expectations, to design and customise the strategic framework for the roadmapping, to develop questionnaires for the research communities involved, and to modify workshop process steps to ensure participation of the entire research community. The workshops brought together academic and industrial experts in the four respective technology areas and involved both offline and online data collection phases. The offline phases were used for data collection from individual participants and publicly available research sources, followed by data consolidation and, where necessary and appropriate, prioritisation. The online workshops were used for data review, analysis and deeper exploration of essential issues. The quality and reliability of the process was maintained by a Steering Committee involving roadmapping facilitators and technical leads from each of the four research communities.

In total, 26 workshops sessions were held across the four technology areas between March 2020 and June 2020. These revealed several materials sub-topics of particular interest for contribution towards the net-zero targets, as well as highlighting important fundamental research and commercial technology enablers that need to be established. These outputs significantly aided research communities' understanding of the future direction of energy materials research, towards the achievement UK's net-zero emission targets by 2050.

Between March and June 2020, over 220 participants contributed to the creation of these five roadmaps from the UK academic and industrial materials communities. The outcomes are:

(1) an **executive summary** report, highlighting the main findings of the four roadmapping activities, published in July 2020;

(2) five **materials development roadmaps** towards net-zero emissions for 2050, published for research communities, funding bodies, government, policy-makers and industry leaders.

The five materials roadmaps generated are living documents, and Royce will engage with research communities regularly to review these documents and to develop further roadmaps as new materials systems and technologies

emerge. We would like to thank all who have participated in these activities through the roadmapping workshops, interviews, surveys and research summaries.

Oversight of these community activities was through the “Materials for the Energy Transition” Steering Group: Professor Neil Alford, (Imperial College London), Professor Manish Chhowalla (University of Cambridge), Professor Richard Curry (University of Manchester), Professor Edmund Linfield (University of Leeds).

Programme management, reporting, and community engagement was undertaken by Royce and IOP: Mia Belfield (Royce), Ellie Copeland (IOP), Anne Crean (IOP), Isobel Hogg (IOP), Judith Holcroft (Royce), Professor David Knowles (Royce), Dr Amy Nommeots-Nomm (Royce), Dr Suman-Lata Sahonta (Royce), Professor Philip Withers (Royce), Dr Katharina Zeissler (Royce).

Roadmapping activities were coordinated by IfM: Dr Nicky Athanassopoulou, Dr Diana Khripko, Dr Imoh Ilevbare, Dr Arsalan Ghani, Andi Jones, Rob Munro.

Technical oversight of roadmaps was undertaken by Dr Oscar Cespedes (University of Leeds), Dr Katharina Zeissler (University of Leeds), Dr Oliver Fenwick (Queen Mary University of London), Dr Robert Hoye (Imperial College London), Dr Xavier Moya (University of Cambridge), Dr Ifan Stephens (Imperial College London), Dr Sam Stranks (University of Cambridge).

EXECUTIVE SUMMARY

The UK has the third largest solar generating capacity (13.1 GW) in Europe after Germany (45.3 GW) and Italy (20.1 GW)[2]. Up to 54 GW of installed solar PV capacity may be needed by 2035 in order to meet net-zero targets, with further growth towards 2050. Along with a range of other renewable and sustainable energy technologies, solar power is anticipated to play a vital role in meeting the UK's priorities of fully-decarbonising buildings, transport, electricity, industry and agriculture[3]. This trend is not unique to the UK; global PV capacity is predicted to reach over 1 TW by 2023, and it is estimated that solar power may provide 70 % of the world's total energy by 2050[4].

Solar cells are expected to become the dominant global electricity generation technology in the coming decades. The recent increase in deployment of solar power has been enabled by the unprecedented fall in manufacturing and deployment costs of market-dominant silicon solar cells over the last decade. There is every expectation that scientific, engineering and manufacturing advances can reduce these costs considerably further. There are various pathways towards reducing costs by implementing improved materials solutions, since the majority of installed solar module costs are due to the panel's mounting system, wiring, switches, DC-to-AC inverters, battery bank, and battery chargers. These Balance-of-Systems (BoS) costs include all costs other than the cost of manufacturing the PV module itself, and improvements in materials solutions for all of these BoS cost factors can allow lower operating costs over the lifetime of a given solar installation.

Current solar modules based on single-junction silicon technology operate at around 20% Power Conversion Efficiency (PCE) of sunlight into electricity. New multi-junction devices (such as perovskite-silicon tandem solar cells) are one possible route to surpassing the efficiency limit of silicon single-junction devices well beyond 20 % PCE, and offer an enormous economic opportunity that can be led by the UK. In the building sector, building-integrated PV (BIPV) can be used as roof tiles, windows and façades, in order to provide integrated power for building heating, hot water and lighting that does not draw from the national grid. Furthermore, innovation in materials science also fosters the development of new, niche applications for solar energy, and drives new emerging markets. For example, solar energy generation is vital for autonomous vehicles, self-powered telecommunications systems, aerospace applications, and for satellites and other space technologies. Also, solar cells can contribute to other high-tech markets, such as indoor-use PV to power Internet of Things (IoT) applications and other emerging home technologies. These niche solar applications are not based on established silicon technologies, where overseas markets dominate, and can therefore enable the UK to take the lead in part-, or even on full-supply-chain manufacturing of new solar materials systems to create diverse new markets.

The UK's research base in providing the fundamental science for driving PV technology is exceptionally strong. Many of the recent key discoveries in the understanding and control of next-generation PV materials (such as organic PV materials and metal-halide perovskites) were made in the UK, and were built on the foundations of the UK's long-standing research base in silicon and thin film semiconductor technologies. The UK can maintain this momentum and deliver further fundamental breakthroughs in materials science, provided that there is sufficient investment.

As well as delivering world-leading fundamental science, the commercial space for the UK to generate new industrial and manufacturing opportunities is significant. Although final-stage manufacturing and module assembly is concentrated in Asia, the value in the materials and components supply chain is already high, and will continue to grow. Examples of UK companies that contribute to the worldwide PV components supply chain include Pilkington/NSG, world-leaders in the production of substrates for innovative thin film PV, and Oxford PV, one of only a few global perovskite-silicon tandem solar cell producers.

[2] EurObserv'ER: https://www.eurobserv-er.org/online-database/#
[3] The Solar Commission: A bright future: opportunities for UK innovation in solar energy - July 2019: https://www.regen.co.uk/wp-content/uploads/The-Solar-Commission-web.pdf
[4] Climate Change Committee, Net-Zero Report 2019: https://www.theccc.org.uk/wp- content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf

When comparing the UK against similarly sized global economies, the UK has demonstrable strengths both in basic science, and in commercial and investment activities, however our translational capabilities between the two are weaker. In particular, we do not have comparable-scale organisations to the National Renewable Energy Laboratory in the USA, the Fraunhofer Institute for Solar Energy and the Helmholtz Zentrum Berlin in Germany, or the Energy research Centre of the Netherlands. Therefore, a major challenge is to provide mechanisms to enable the UK community to accelerate the translation of materials science discoveries and developments into deployable technologies.

Significant new renewable generation capacity is needed in the UK to meet domestic demand and to accommodate uptake of electric vehicles and hybrid heat pumps in the coming decade, whilst maintaining a pathway to net-zero greenhouse gas emissions by 2050. The UK Committee on Climate Change predicts that 645 TWh/year[5] of electrical energy from low-carbon generation sources is needed by 2050 (compared to 155 TWh/year of energy from low-carbon generation sources today) in order to meet the UK's net-zero CO_2 emissions targets. Currently, PV only contributes 13 TWh/year of electrical energy to the National Grid, but there is potential to increase this by a factor of 100 by increasing the UK's solar generation capacity along with integrated energy storage technologies, allowing the majority of the UK's energy needs to be met by PV alone[6]. Achieving this will require a combination of refining industrially-established PV materials (i.e. silicon and thin film cadmium telluride and selenide technologies), as well as developing emerging materials and implementing new device structures that allow higher efficiencies to be achieved.

By bringing together academic and industrial experts from different research fields related to developing materials in PV systems, the aim of this materials roadmapping study was to provide answers to the following questions:

1. How can existing and new PV materials develop over the next 30 years to accelerate PV deployment in line with the goal of carbon neutrality by 2050?
2. What are the materials challenges for established and emerging PV materials?
3. Which materials are needed for niche applications that could enable new UK-led markets?

In order to assess the full landscape of material science in photovoltaics in the UK, and to answer the questions formulated above, members of the UK photovoltaics research community were invited to explore different aspects of established and new materials, technologies and applications in photovoltaic systems. The following two subsections provide a high-level summary of the identified academic research needs and the industrial challenges regarding deployment and/or commercial upscaling, both for established PV materials and for emerging materials.

Established PV Materials

The **current state-of-art** solar technologies on the market are well-established crystalline silicon solar cells and cadmium telluride-based (CdSeTe/CdTe) thin film solar cells. Due to their low-cost manufacture and global market saturation, established technologies will remain important for the UK's future solar market beyond 2050.

The main outcomes of materials roadmapping for established PV systems i.e. silicon and thin film cadmium telluride-based systems are outlined as follows.

The module efficiency of **silicon solar cells** can be increased, and their levelised cost of energy (LCOE) reduced to accelerate their deployment, by addressing the following **key challenges and research needs**:

[5] UK Committee on Climate Change, *Net Zero: The UK's Contribution to Stopping Global Warming* (2019)
[6] https://solargis.com/maps-and-gis-data/download/united-kingdom

- Extension of device lifetime to 40 years from current values of around 25 years, and achieving improved and stable charge-carrier lifetimes by eliminating light- and temperature-induced degradation of the solar module materials
- Reduction of the thermal budget of manufacturing silicon PV by developing lower-temperature cell processes that emit less CO_2 (current silicon PV emissions are around 40 gCO_2e/kWh[7])
- Development of novel methods of *in operando* characterisation for real-time monitoring
- Tailoring silicon cells for high-efficiency structures, e.g. as bottom cells in tandems with perovskites
- Short-term development of bifacial silicon solar cells to increase light collection, which can increase efficiencies by up to 20%. Further advanced development is required to increase bifaciality from 70% to 100% to enable new PV system array designs to be exploited (e.g. vertically-mounted solar modules that enable early morning and late afternoon solar generation)
- Development of low-cost metallisation, i.e. replacement of conducting silver paste with abundant and low-cost alternatives
- Recycling of modules and recovering high value components

After silicon, the second most common photovoltaic systems are based on cadmium telluride. These are of interest for low capital-intensity solar cell systems. The **key challenges for early-stage research** in this technology are:

- Development to increase single-junction cell efficiencies to 25 %, and development of bifacial and tandem devices reaching 32 % efficiency
- Improvement in carrier lifetimes through Group V doping and improved surface passivation
- Manipulation of defect states and improved defect reduction strategies to enhance device performance
- Development of strategies to mitigate the potential toxicity and scarcity of the elements used in CdTe-based PV e.g. indium, tellurium and cadmium. There is insufficient global tellurium production (and possibly insufficient global reserves) to meet future CdTe-based PV demand. Thus, advanced life cycle analysis is required.

The key **commercial challenges** for established PV systems are:

- Identification of the causes and mitigation of potential induced degradation
- Reduction of cover glass soiling which reduces solar power output by 10 % in the UK
- Improvement of AC/DC conversion efficiencies for solar inverters
- New protocols for accelerated degradation testing of new materials
- Investment in TRL 3 and 4[8]

All of the above early-stage and commercial challenges for established PV technologies will be relevant for emerging PV technologies as they mature.

New PV Materials and Applications

New materials in PV systems were classified into three categories:

I. Perovskites and perovskite-inspired materials
II. Organics and dye-sensitised solar cell materials
III. Emerging and established inorganic materials and emerging thin films

[7] NREL, https://www.nrel.gov/docs/fy13osti/56487.pdf
[8] Technology readiness level at a stage, where proven technology in the lab starts to be developed at an industrial level, specifically for PV it means moving from the cell level (done in the lab) to the module level (needed in industry)

Different materials systems and device design concepts that are applicable at utility level, including rooftops and/or niche applications, were identified within each of these three materials categories. In the following, the main challenges and research needs for some of the new materials technologies and device design concepts are explained.

Across all technologies, a critical factor will be the stability of the absorbers, devices and modules. This will require consensus on stability testing and reporting protocols to ensure consistency and reproducibility between laboratories, dedicated national facilities for state-of-the-art stability testing, and the development of accelerated degradation tests for new absorbers.

A. **Multi-junction technologies** (perovskite-silicon and all-thin film tandem cells) for large-scale solar generation modules. They may also be used for a range of smaller-scale applications. There is a need to develop:

    1) **all-thin film tandem solar cells**, which have the potential for much lower capital costs for rapid scale up manufacturing and deployment[9], as well as

    2) **triple-junction tandems**, which can achieve significantly higher efficiencies.

    A desired UK solar-powered future includes 35 % efficient perovskite-silicon tandem modules with 40-year lifetime and £4/MWh LCOE. For thin-film tandems, a scenario allowing for shorter device lifetimes than 40 years is possible if module replacement schemes are implemented, whilst still maintaining low LCOEs. Together with growing Si-based deployment, there is potential for these new technologies to push total PV generation capacity to 50 % by 2030.

    The main challenges and research needs are:

    - Stabilised bandgaps for thin film tandem structures
    - Sustainable manufacturing routes, e.g. the use of non-toxic source materials
    - Sustainable and inexpensive transparent conducting oxides, metallisation and packaging. This includes replacing silver and gold contacts with cheaper materials, e.g. copper or carbon

B. **Single-junction perovskites** are an approach for efficient future applications such as building-integrated photovoltaics (BIPV) e.g. solar cell windows, indoor PV for generating power from artificial lights. BIPV is of importance to net-zero goals since it will contribute to CO_2-neutral buildings with solar power for domestic uses, envisioning that the BIPV will last over the duration of the building. BIPV can be used as roof-tiles, windows, façades, car-porches, industrial/agricultural buildings, greenhouses or in automotive applications.

    Single-junction perovskites are also of interest for utility-scale PV applications such as solar-powered heating for the home. They can be used in high-efficiency solar cell modules with low capital-intensity and low light inputs. They also can be integrated with other technologies, such as for solar fuel generation, ammonia generation, and solar water-splitting.

    General challenges and research requirements for single-junction perovskites are:

    - Sustainable and inexpensive transparent conducting oxides
    - Research into the passivation of perovskite films and improving the stability against environmental and operational degradation. This requires a focus on both the fundamental science (theory and characterisation), and module engineering (scale-up)
    - Focus on module design and achieving high efficiency in large-scale solar modules

[9] DOI: 10.1039/C6EE00484A

The main challenges and research re specific to BIPV integration are:

- Scale-up and solar module manufacturing, along with transportability to building site
- Sustainable and inexpensive transparent conducting oxides with high light transmittance (as close as possible to 100 %) with low sheet resistance
- Understanding how environmental changes affect solar cell performance (e.g. dirt, cleaning).

C. **Mobile PV applications** are essential for use in autonomous vehicles, aerospace, telecommunications, and space applications such as satellites. New materials can be deposited on flexible substrates, which can be more easily integrated with automotive and satellite systems that require high power densities.

The main challenges and research needs are:

- Radiation tolerance of PV materials needs to be understood, with high device reliability over a defined duty cycle
- Further development of stability and performance of relevant materials (including multi-junctions), including perovskites, organics, and III-V photovoltaic materials
- Development of inexpensive transparent conducting oxides

D. **Standalone PV applications** are required for indoor solar power or for autonomous small devices (e.g. Internet of Things).

The main challenges and research needs are:

- Sustainable and inexpensive transparent conducting oxides
- Manufacturing of materials using low-toxicity solvents
- Scale-up of device area
- Encapsulation of indoor devices, for example for flexible devices
- Development of optical structures to improve the management of light into the device
- Materials include: organic photovoltaic materials, dye-sensitised solar cells, perovskites, and emerging inorganic materials

Requirements and opportunities across established and emerging materials and applications

Key challenges in emerging PV, especially to facilitate translation of lab-based research into commercial scaling up to terawatt-scale, and to capitalise on UK-developed and UK-led technologies, are:

- Stability and reliability of the PV materials and device material layers
- Development of encapsulation and packaging materials (both cell and edge sealants)
- Development of new types of transparent conducting oxides that are composed of abundant, low-cost elements
- Full life-cycle assessment to determine sustainability of new materials
- Capital and variable costs of scalability and manufacturability

The following **research and technology developments** were identified for the different PV technologies:

- Central testing facilities for TRL 3 and 4 testing, as well as industrial scale-up, including personnel to develop protocols for high-level outdoor and accelerated indoor environmental degradation testing, operational lifetime testing, and testing of adhesive and lamination strength to ensure the safety of BIPV
- Dedicated UK-based cell processing laboratory facilities to tailor and innovate silicon devices, e.g. perovskites tandems
- Broad training in technical skills, facility operation, research skills (e.g. doctoral training in photovoltaics) are needed to build up the UK's pipeline and number of skilled people in the field
- Consortia bringing academia, industry, asset managers, Innovate UK and international world leaders in solar technologies (e.g. First Solar, NREL and Fraunhofer ISE) are needed to exploit potential for growth of emerging solar markets in UK
- Availability of advanced *in situ* and *in operando* characterisation equipment for PV materials to understand operation and degradation pathways from atomic level right up to module level e.g. microwave photo-conductance, sunsV_{oc}, advanced microscopy techniques. This will also require staff and technicians to maintain the equipment, perform measurements and train new users
- Life Cycle Analyses of PV materials are needed to ensure sustainable manufacturing, low toxicity of the materials and precursors, with the aim of technologies recyclable

The following **commercial enablers** were identified for the different PV technologies explored:

- Regulation for carbon-neutral buildings in order to encourage BIPV uptake on greater than 10 % of new-builds
- Large-scale manufacturing technologies need to be developed, using inexpensive raw materials and sustainable processing routes, e.g. development of non-toxic solvents for processing
- A techno-economic analysis of large-scale manufacturing for is required across all technologies, and particularly for cadmium telluride systems, as this is a mature technology that may be suitable for further deployment
- Support for SMEs in the solar power sector e.g. funding and investment opportunities, academic-industry programmes

Conclusions

The above priorities, targets and enablers have been identified by the research community to help achieve a range of PV solutions, from enabling over 50 GW grid-scale solar capacity, to development of zero-carbon buildings, and solar power-integrated automotive applications. These capitalise on the UK's strong base in early-stage research in PV, and focus on linking this with downstream industry scale-up and commercial translation opportunities. Stronger links between low and medium TRL levels can enable the UK to take advantage of materials technologies for niche applications, which in turn will allow access to new PV markets and secondary supply chains.

THE UK'S SOLAR PV MARKET

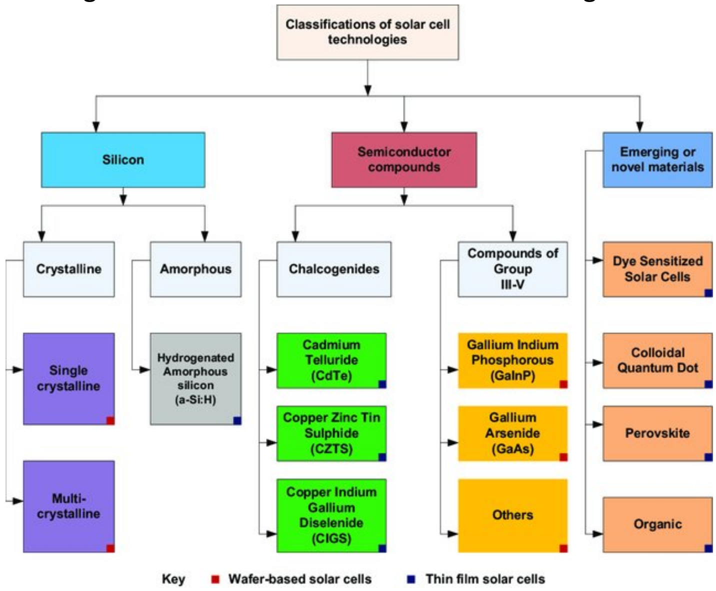
The UK government is committed to achieving net-zero greenhouse gas emissions by 2050. For this to occur, significant reductions in emissions must be demonstrated by 2035. Around 21% of greenhouse gas emissions in the UK are from power generation, which is still largely based on natural gas, oil and coal. Within the UK, as coal power stations close by 2025, significant new renewable generation capacity is needed to meet domestic demand and to accommodate uptake of electric vehicles and hybrid heat pumps.

The UK Committee on Climate Change predicts that 645 TWh/year[10] of electrical energy from low-carbon generation sources is needed by 2050 (compared to 155 TWh/year low-carbon generation sources today) in order to meet the UK's net-zero CO_2 emissions target. Currently, solar energy generation only contributes 12.7 TWh/year to the National Grid[11], but there is potential to increase this by a factor of 100[12]. Achieving this will require a combination of improving industrially-established PV materials (silicon and thin film cadmium telluride-based PV), as well as developing emerging materials and new device structures that allow higher efficiencies to be achieved.

STATE OF THE ART OF PV TECHNOLOGIES

The figure below summarises all solar cell materials classes. Silicon PV is the basis for first-generation solar cells.

Figure 1: Classification of solar cell technologies [13]



The current state-of-the-art solar technologies on the market are crystalline silicon (c-Si) solar cells and thin film cadmium telluride-based CdSeTe/CdTe solar cells, with a 94.5% and 5.5% market share respectively. Crystalline silicon solar cells account for global energy production greater than 150 gigawatts of electrical energy at peak (GWp). Average solar module cost was $0.24/Wp (as of end of 2018). The world record solar conversion efficiency is 26.7% (Kaneka *et al.* 2018) for a crystalline silicon laboratory test cell[14].

[10] UK Committee on Climate Change, *Net Zero: The UK's Contribution to Stopping Global Warming* (2019)
[11] BEIS https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf
[12] https://solargis.com/maps-and-gis-data/download/united-kingdom
[13] https://www.researchgate.net/publication/317569861_Perovskite_solar_cells_An_integrated_hybrid_lifecycle_assessment_and_review_in_comparison_with_other_photovoltaic_technologies/figures?lo=1

[14] NREL, https://www.nrel.gov/pv/cell-efficiency.html

Traditional aluminium back surface field (Al-BSF) technology has been displaced by passivated emitter and rear cells (PERC). There are two main commercial silicon wafer types (monocrystalline and multi-crystalline) and until recently both have had significant market shares, but monocrystalline PERC is expected to dominate in the short term. High quality commercial panels are typically 22-24% (monocrystalline) or 18-20% (multi-crystalline), although there are significant outliers depending on manufacturer and technology. Silicon heterojunction cells (SHCs) have a small market share, but are used as the base cells for perovskite-silicon tandems. More advanced cell structures such as interdigitated back contact (IBC) cells are available, but are not currently mainstream. Today's solar cell modules are extremely reliable and are typically shipped with 25- to 30-year power warranties. Bifacial cells that collect light from both front and rear surfaces of a cell can boost electricity production from PV panels by up to 20% depending on climate and ground conditions, and manufacture of these products has been enabled by the availability of low-cost high-quality wafers. For utility-scale applications in the UK, LCOE is around £67/MWh in 2020[15]. Carbon Footprint over the whole life cycle (cradle-to-grave) of crystalline silicon PV cells is around 40 gCO_2e/kWh[16], and its energy payback time can be 3 to 7 (several locations).[17] CdTe is the lowest cost current technology at around $0.30/Wp. First Solar produces 6 GW of CdTe solar modules per annum, using 60 sq km of coated glass supplied by Pilkington/NSG.

Despite the UK being world leading in PV technology research, large scale manufacturing is located overseas. China is the largest manufacturer of crystalline silicon solar cells, with at least four Chinese manufacturing companies with >10GW shipments. Because silicon and cadmium telluride have achieved massive-scale manufacturing, the market entry barriers at a utility scale for any new PV materials technologies are huge.

Due to their availability and low cost, established technologies will remain important for the UK's future solar market. Due to the scale of deployment, there are still opportunities for increasing the performance of both Si and cadmium telluride solar cells where even small efficiency increases in silicon solar cells would have a significant impact on the global PV market. There are also opportunities for improvements, for example, in bifacial soar cell efficiencies. Thus, the technological and commercial challenges for existing technologies (see Section: Materials Challenges Across Technologies) can be addressed by further improvements in performance, as well as by the development of new materials systems and improved device design concepts. In addition to offering higher efficiencies than silicon PV systems, new solar materials can be grown on flexible substrates, allowing new form factors and new opportunities for device design. Through use of low-cost fabrication methods which involve substantially less capital expenditure, growth of the PV market can take place sustainably at a sufficient rate to ensure that large-scale deployment is possible. Nevertheless, a variety of research and development challenges need to be overcome for new and emerging PV materials.

PROBLEM STATEMENT

The UK has world-leading capability in research and development into photovoltaic materials. However, it does not currently have any manufacturing capacity for solar cells and there is currently a very challenging environment for commercialising new technologies compared to other nations. Addressing this situation will be critical to ensure that:

1. The UK captures a larger fraction of the world's PV market at the utility level (worth £120B worldwide[18]), and in niche areas such as building-integrated photovoltaics (worth >£1B worldwide[19]) and indoor

[15] BEIS, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566567/BEIS_Electricity_Generation_Cost_Report.pdf ; also (2) Jäger-Waldau, A., PV Status Report 2019, JRC Science for Policy Report, https://ec.europa.eu/jrc/sites/jrcsh/files/kjna29938enn_1.pdf
[16] (1) NREL, https://www.nrel.gov/docs/fy13osti/56487.pdf ; (2) Mariska de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems December 2013Solar Energy Materials and Solar Cells 119:296-305, DOI: 10.1016/j.solmat.2013.08.037
[17] (1) Saïcha Gerbinetn, Sandra Belboom, Angélique Léonard, Life Cycle Analysis (LCA) of photovoltaic panels: A review , https://doi.org/10.1016/j.rser.2014.07.043 ; (2) R.H.E.M. Koppelaar, Solar-PV energy payback and net energy: Meta-assessment of study quality,reproducibility, and results harmonization, https://doi.org/10.1016/j.rser.2016.10.077 (3) Khagendra P.BhandaribJennifer M.CollieraRandy J.EllingsonbDefne S.Apula, Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis, (EROI) of solar photovoltaic systems: A systematic review and meta-analysis, https://doi.org/10.1016/j.rser.2015.02.057 ; (4) Mariska de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems, December 2013 Solar Energy Materials and Solar Cells 119:296-305, DOI: 10.1016/j.solmat.2013.08.037;
[18] https://www.grandviewresearch.com/industry-analysis/solar-panels-market?utm_source=prnewswire&utm_medium=referral&utm_campaign=cmfe_18-jun-20&utm_term=solar-panels-market&utm_content=rd1
[19] DOI: 10.1016/j.joule.2019.03.026

photovoltaics (worth >£100M worldwide[20] and set to increase as IoT and other sensor applications become increasingly more common).
2. Innovations into new solar technologies made in the UK can progress from start-ups towards establishment as large companies.
3. The energy security of the UK is maintained, and where the significant future demand for PV-based energy generation can be met locally
4. The demand for a new generation of PV scientists and engineers can be met locally

Nurturing local expertise in photovoltaics science and engineering, and investing in routes to commercialise new innovations and technologies will be critical to achieving net-zero carbon emissions targets, as well as bringing economic benefits to the UK, in terms of generation of new markets, supply chains, and energy sector jobs.

AIMS

The aim of the materials roadmapping workshops was to explore PV materials and systems that can enable the UK to meet its goal of net-zero greenhouse gas emissions by 2050. This includes methods of improving performance, costs and lifetimes of new technologies, such as perovskite-based solar cells, as well as the current state-of-the-art in the market, namely crystalline silicon and cadmium telluride-based thin film solar cells. Academic and industrial experts from different PV research fields were brought together to discuss the following questions:

1. How can existing and new PV materials develop over the next 30 years to accelerate PV deployment and achieve carbon neutrality by 2050?

2. What are the materials challenges for established and emerging PV materials?

3. Which materials developments are needed for niche applications that could enable new UK markets?

Specific research questions and challenges in each of these areas must be addressed, in order to enable the development and adoption of existing and new materials to make step-changes in PV technologies to reach net-zero emissions by 2050. In particular, it is essential to address how research infrastructure in the UK could be improved to accelerate the commercialisation of these new materials.

The overall objective of this project is to develop a preliminary roadmap that can be used to guide discussions with PV research communities, the PV industry and government. Specifically:

- Understand the current state-of-the-art in each area of interest;
- Define in detail the key current challenges for each area that present barriers to meeting UK's net zero targets;
- Define in detail the anticipated future challenges for each area that present barriers to meeting UK's net zero targets;
- Identify and prioritise the best solutions to these challenges that can make step-changes in research to reach 2050 targets;
- Identify the desired performance targets of these solutions.

In total 50 key stakeholders from 34 academic institutions/national labs and 10 UK-based companies from across the UK attended a series of 5 workshops. Small groups of stakeholders also submitted additional

[20] DOI: 10.1016/j.joule.2019.03.026

written input, and gave feedback on roadmapping data and reports. There was balanced representation from both academia and industry.

AREAS INVESTIGATED AND MATERIALS ROADMAPS

Emerging PV materials beyond silicon and CdTe-based PV can be used for utility scale and rooftop PV, as well as for niche applications. Nevertheless, silicon will remain the main deployed PV technology in the UK towards 2050. PV materials were split into four main categories, for which current and future device design concepts, research challenges, and enabling technologies were investigated:

1. Perovskites and perovskite-inspired PV materials
2. Organic PV materials and dye-sensitised solar cells
3. Emerging inorganic PV materials
4. Established PV technologies and some selected new materials

Figure 2, Figure 3 and Figure 4 display the first step of the analysis perovskite PV, organics and dye-sensitised solar cells, and emerging inorganic PV materials. Each roadmap covers three time periods: the short term (next 5 years i.e. up to 2025), the medium term (next 15 years, i.e. up to 2035) and the long term (next 30 years, i.e. up to 2050). Roadmaps include two broad layers: (1) the materials system and device design concepts, and (2) research challenges, enabling technologies, and other enablers. The first layer is further subdivided into three sub-layers:

- Utility scale and rooftop
- Niche applications
- Both

The second layer is also subdivided into three sub-layers:

- Research challenges
- Enabling technologies
- Other enablers

In total, 55 materials system and device design concepts, 76 materials-specific research challenges, and 74 general research challenges and enablers (shown in Appendix V) were identified and discussed further during the workshop series.

Figure 2: Halide perovskites and perovskite-inspired PV materials

<table>
<tr><th colspan="2"></th><th>Short term
until 2025</th><th>Medium term
2025 - 2035</th><th>Long term
2035 - 2050</th></tr>
<tr><td rowspan="12">New materials systems and device design concepts</td><td rowspan="5">Utility scale and rooftop</td><td colspan="2">Single junction Perovkites - Flexible</td><td></td></tr>
<tr><td colspan="2">Mobility charge transport materials (including organic electron transport materials for tandem configurations)</td><td></td></tr>
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<tr><td></td><td></td><td>Triple junction perovskite cells with Si</td></tr>
<tr><td></td><td></td><td>Triple junction silicon plus two perovskite</td></tr>
<tr><td rowspan="2">Niche application</td><td colspan="2">Single junction Perovkites - Glas mounted (Note: All printable version – 3 layers (Manufactured in China); There is a good potential for this material)</td><td>Semintransparent perovskite solar cells (Note: Car windows application; Build technologies; Colour issues need sorting)</td></tr>
<tr><td colspan="2">Perovskites for indoor PV (Note: Relating to IoT power scavenging; not limited to wide-band gap)</td><td></td></tr>
<tr><td rowspan="5">Both</td><td>Perovskite-Si tandem cells / Perovskites/Si concept utilising wide bandgap perovskites (Note: Can be flexible or rigid; Applications:- Radiation tolerant; space application; building integration)</td><td></td><td></td></tr>
<tr><td colspan="2">Lightweight, high power perovskite-perovskite or perovskite-CIGS tandem cells (Note: Automotive application; Cost dimensions are important especially capital outlay and production cost; Perovskite Si)</td><td></td></tr>
<tr><td></td><td colspan="2">Lead free perovskite-perovskite (or perovskite-like) tandems</td></tr>
<tr><td></td><td>Flexible, printable PVs with lower transportation costs (Note: Single junction; Form factor; high volume manufacturing; Ultra Low Cost PV – Flexible Printable; Manufacturing techniques – highly scable; Competition from other tech (non Flex))</td><td></td></tr>
<tr><td colspan="3">Perovskites organic and tandem with organics</td></tr>
<tr><td rowspan="20">Research challenges, enabling technology, other enablers</td><td rowspan="16">Research challenges</td><td colspan="3">Direct generation of NH_3</td></tr>
<tr><td colspan="2">Stabilising current materials and contacts promising for tandems</td><td>Elimination of lead compounds in perovskite</td></tr>
<tr><td></td><td>Developing new lead-free absorbers that are efficient and stable</td><td></td></tr>
<tr><td colspan="2">Stable band gaps ~2 eV in perovskites</td><td></td></tr>
<tr><td colspan="2">Stable, long lifetime low band gap perovskites for perovskite-perovskite tandems</td><td></td></tr>
<tr><td colspan="3">For T1-10: Semintransparent perovskite solar cells (Note: colour issues need to be addressed)</td></tr>
<tr><td colspan="3">Perovskite devise offer high efficiency, and there is a lot of work done to improve stability. But the work on stability needs improved consistency between labs. This can be addressed by the community adopting and adhering to stability measurement protoco</td></tr>
<tr><td colspan="3">Hybrid Si perovskites - sprayable and can be ink-jet printed</td></tr>
<tr><td colspan="3">Hybrid Si perovskites - low energy input costs</td></tr>
<tr><td colspan="3">Perovskites, increasing stability is a major challenge, together with development of low cost encapsulation techniques.</td></tr>
<tr><td colspan="3">Perovskites - Reducing the toxicity of the materials (i.e. lead, tin) and the solvents used to process materials is also a concern.</td></tr>
<tr><td colspan="3">Instability of the material of lead-halide perovskites</td></tr>
<tr><td colspan="3">Identifying lead-free alternatives lead-halide perovskites</td></tr>
<tr><td colspan="3">Perovskites - stability in air and easy recycling</td></tr>
<tr><td colspan="3">Properties: Flexible, lightweight, transparent, conductive substrates with low series/charge-transfer resistance for flexible devices (Avoiding ITO).</td></tr>
<tr><td colspan="3">Developing transparent p-type conductive oxides for tandem cells</td></tr>
<tr><td rowspan="3">Enabling Technology</td><td rowspan="2">Development of native state perovskite characterisation at critical length scale <10 nm for defects, interfaces, grain boundaries, strain fields, which are inaccessible to X-Ray techniques. Productivity enhancements of tandem cell production</td><td>Achieve neutral colour semitransparent perovskite solar cells in large scale R2R production</td><td></td></tr>
<tr><td>Replacement of silver with copper metalisation</td><td></td></tr>
<tr><td colspan="2">Achieving 25-year stability with perovskite modules</td><td></td></tr>
<tr><td>Other enablers</td><td colspan="2">Directed funding for exploratory materials and interface exploration/validation</td><td></td></tr>
</table>

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<tr><td colspan="3">Perovskites organic and tandem with organics</td></tr>
<tr><td rowspan="21">Research challenges, enabling technology, other enablers</td><td rowspan="17">Research challenges</td><td>Built in capture system for Pb in event of failure and water ingress</td><td>Direct generation of solar fuel</td><td></td></tr>
<tr><td colspan="3">Direct generation of NH3</td></tr>
<tr><td colspan="2">Stabilising current materials and contacts promising for tandems</td><td>Elimination of lead compounds in perovskite</td></tr>
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<tr><td>Other enablers</td><td colspan="2">Directed funding for exploratory materials and interface exploration/validation</td><td></td></tr>
</table>

Figure 3: Organic PV materials and dye-sensitised solar cells

		Short term until 2025	Medium term 2025 - 2035	Long term 2035 - 2050
New materials systems and device design concepts	Utility scale and rooftop			
	Niche application	Ultra-High Power Density for UAV / Mobile Power		
		IR specific (VLT transparent) Donor and Accceptor molecules		
		Single sided OPV - electrodes and transfer layers on one side		
		Dye-sensitised solar cells		
		Hole transport layer (HTL) (inverted Organic PV device)		
		Carbon dots		
	Both	Large Monolithic Area (Not Serial Interconnection)		
		Single molecule OPV		
		Scalable (in terms of production) non-fullerene acceptors		
		Organic tandem solar cells		
			Operationally stable solar cell devices (Stability of materials and stack and between individual mats)	
			Complementray Absorber Single Junction	
		Graphene or other non-conventional materials such as carbon nanotubes		
		Organic semiconductors and micro batteries		
		Single component photo-active (PA) layers		
		Organics to complement silicon		
		Transparent and Selective electrodes (common to all SC; flexibility is required)		
		Light management		
Research challenges, enabling technology, other enablers	Research challenges	Transparent bus bars		
		Morphology control in blended heterojunctions		
		Production equipment		
		Inexpensive flexible encapsulation		
		Recycling		
		Manufacturing technologies at scale		
		Design for systems level		
		For organics, efficiency needs to be improved, together with reducing the cost of material synthesis and purification. Operational stability is still a big issue.		
		OPV suffers from poor adhesion between PA and PEDOT:PSS - need a suitable replacement that is not deposited by evaporation		
		3D morphology for carrier lifetime/pathlength - especially for OPV - additives etc…		
		Exciton binding energy penalty		
		Making these materials in large enough quantities for large-scale deployment		
		Further work to increase power conversion efficiencies through device structure and new materials design		
		Properties: Flexible, lightweight, transparent, conductive substrates with low series/charge-transfer resistance for flexible devices (Avoiding ITO).		
	Enabling Technology	New patterning and deposition methods (low temperature)		
		Non-flat surfaces and non-plastic/glass surfaces		
		Low sheet resistance, low cost TCE		
		Stability AM1.5 and AM1.0		
	Other enablers			

Figure 4: Emerging inorganic PV materials

<table>
<tr><th></th><th></th><th>Short term
until 2025</th><th>Medium term
2025 - 2035</th><th>Long term
2035 - 2050</th></tr>
<tr><td rowspan="23">New materials systems and device design concepts</td><td rowspan="7">Utility scale and rooftop</td><td colspan="3">CIGS (copper indium gallium selenide solar cell)</td></tr>
<tr><td colspan="3">Inorganic thin film materials - CdTe</td></tr>
<tr><td></td><td>Improved materials for carrier selective contacts compatible with industrial processing of silicon</td><td></td></tr>
<tr><td colspan="3">Semiconductor photon detectors for the far infrared region of the spectrum and night vision</td></tr>
<tr><td colspan="3">Wide band gap semiconductors to improve inverters in PV installations that are a key cause of failures</td></tr>
<tr><td colspan="3">Inorganic thin film for a tandem configuration with silicon</td></tr>
<tr><td></td><td colspan="2">Tandems between wide band gap emerging materials and silicon</td></tr>
<tr><td rowspan="8">Niche application</td><td colspan="3">Solar cells designed for use under such high concentrations—called multi-junction cells</td></tr>
<tr><td colspan="2">PV with diversified appearance for BIPV</td><td></td></tr>
<tr><td colspan="2">PV with diversified appearance for indoor & consumer</td><td></td></tr>
<tr><td colspan="3">GaAs</td></tr>
<tr><td colspan="3">GaAlAS (or other combination of III-V group elements) fabricated in multilayer structures using Metalorganic-Vapour- Phase Epitaxy (MOVPE)</td></tr>
<tr><td>Quantum dot-based solar cells, e.g. based on depleted heterojunction</td><td></td><td>Vacancy ordered perovskites</td></tr>
<tr><td colspan="2">Indoor PVs for IoT and building-integrated PV (taking advantage of the colours of the materials)</td><td></td></tr>
<tr><td colspan="3">Quantum dot solids</td></tr>
<tr><td rowspan="8">Both</td><td colspan="3">Single component photo-active (PA) layers</td></tr>
<tr><td></td><td colspan="2">Defect tolerant semiconductors, e.g.: bismuth-based materials</td></tr>
<tr><td colspan="3">CZTS (copper zinc tin selenide) cells</td></tr>
<tr><td></td><td></td><td>Chalcogenides</td></tr>
<tr><td></td><td></td><td>Binary and tenary halides</td></tr>
<tr><td></td><td></td><td>Chalco halides</td></tr>
<tr><td colspan="3">New materials for hole extraction–charge transport layers</td></tr>
<tr><td>New transparent conducting oxides (common to all thin film technologies; New dopants for ITO etc.)</td><td></td><td></td></tr>
</table>

Emerging inorganic PV materials (continued)

Research challenges, enabling technology, other enablers		Short term until 2025	Medium term 2025 - 2035	Long term 2035 - 2050
	Research challenges	Stability of materials		
			A manufacturing process for kerfless silicon wafers	
			Replacement of silver for contacts (e.g. with copper)	
			Intergration of silicon into commercially viable tandem technologies (e.g. with perovskites)	
		2 losses from solar cover glass – 1. Anti-reflection coating and 2. Anti-soiling – possibility with hydrophobic coatings?		
		Durable and low cost anti-reflection coatings for the cover glass		
		Super-hydrophobic coatings to reduce soiling (soiling reduces the power output by 10% in the UK to 50% in MENA counties).		
		Coatings for the cover glass to increase IR reflection to reduce module temperature		
		These would benefit from UK manufacturing opportunities		
		CdTe research challenges: Group V doping of the absorber to improve carrier lifetimes		
		CdTe research challenges: Optimisation of Se grading at te front of the cell.		
		CdTe research challenges: Development of a stable buffer layer above the TCO with good band alignment		
		CdTe research challenges: Improved TCO's. Reduced optical absorbtion.		
		CdTe research challenges: Current champion cell efficiency is 22.1% (module efficiency is 19%); 25% cell efficiency possible by 2025.		
		CdTe research challenges: Tandem CdTe based solar cells with band gaps engineered by alloying.		
		Direct generation of solar fuel (or NH3) using catalyst attched to QD		
		Inverse design of defect tolerant semiconductors		
		New tools to accelerate the optimisation of transport properties		
	Enabling Technology	Processing and scale up		
		Reducing wafer thickness		
		Reducing kerf losses		
		Integrated QD-based LED emission/reabsorption, ink jet prinitng on curved glass, e.g. ink jet printing on curved glass		
	Other enablers	Large scale ALD to grow Al2O3 passivation layers for PERC		
		Linking together (computational, robotics) materials discovery, machine learning and device development		
			Low CAPEX (including lower temperatures), scalable manufacturing/deposition methods	
		Standards for characterising materials for PV applications		
		Better encapsulants and adhesive materials		
		Flexible and non-standard substrates		
		Access to equipment for measuring the long-term stability of devices		
		Definition of protocols and reporting (standardisation) for reporting the long-term stability of devices		

EXPLORATION OF MATERIALS

The detailed exploration of established and emerging PV materials systems and device designs aimed to define the scope of PV research, and to identify desired performance characteristics to map the development path for all major PV technologies towards 2050. Based on the academic and industry research community discussions during the roadmapping workshops, particular established technologies and new materials were selected for exploration:

- Crystalline silicon PV
- Thin film CdSeTe/CdTe systems
- Single junction perovskite PV
- Perovskite-silicon tandems and other multi-junction devices
- All PV and related structural/packaging materials for BIPV applications
- PV devices for standalone mobile energy sources
- Terrestrial and space mobile energy sources

The scope of research, specific research challenges, industrial R&D activities, required competences and resources, and deployment barriers were explored for the materials systems listed above, and are tabulated below in the following roadmaps.

CRYSTALLINE SILICON

Silicon-based PV has been developed over the past 60 years. With ~94.5% market share, crystalline silicon currently dominates the UK solar market[21] and is the only technology worldwide that is capable of supplying a significant proportion of national energy needs[22]. The scale of silicon is vast, and getting to this point has taken many years. Therefore, under consideration of UK's internationally-competitive position in silicon materials research, silicon will be at the centre of the short- to medium-term PV strategy for achieving the UK's zero carbon goals in the next 20 years. Silicon is also likely to be the first substrate of choice for tandems (e.g. perovskite on Si as those produced by Oxford PV). As such, silicon PV is a vitally important research area for the UK (and the rest of the world).

The issues with silicon technology are different from those of newly-emerging technologies. The efficiency enhancements in silicon will be smaller, but small improvements will have a huge global impact. Therefore, this topic is focused on the further development of all materials aspects of crystalline silicon solar cells: materials, surfaces/interfaces, cell fabrication, manufacturing etc. Important research areas for the future of this technology are specifically related to the improvement of silicon materials, and cell architectures for bifacial and tandem solar cells, as well as the junction between silicon and other parts of the tandem cell. Further challenges and research needs are:

- Extension of the device lifetime of existing PV materials for terrestrial applications from around 25-30 years to 40 years, and achieving improved and more stable charge-carrier lifetimes by eliminating light- and temperature-induced degradation
- Single crystal silicon solar cells demand very high temperatures in order to melt silicon pieces to create single crystals, resulting in high CO_2 emissions from the silicon PV industry (currently at ~40 gCO2e/kWh[23]). This process is unlikely to be changed, but reduction of the total thermal budget by developing lower temperature processes elsewhere in silicon cell manufacture, that still enable high performance to be achieved, will lead to a reduction in emissions.

[21] https://www.regen.co.uk/wp-content/uploads/The-Solar-Commission-web.pdf
[22] https://www.sciencedirect.com/science/article/pii/B9780080878720001177
[23] NREL, https://www.nrel.gov/docs/fy13osti/56487.pdf

- Development of novel methods for in situ and in operando materials and device characterisation to aid translation to scale-up facilities
- Tailoring silicon cells for high-efficiency structures, e.g. as bottom cells in tandem with perovskites
- Development of advanced materials and device metrology methods for commercial testing, such as characterisation of potential-induced degradation in full devices
- Further development of bifacial silicon solar cells, where the front and back sides of the solar cell module is exposed to light. This can increase energy conversion efficiencies by up to 20%. Further development is needed to increase the energy conversion efficiency of the back side of the bifacial module from 70% to 100%, by exploiting new PV system array designs (e.g. vertically-mounted solar cell modules that enable early morning and late afternoon solar generation).
- Deployment of low-cost metallisation e.g. elimination of silver paste with cheaper metals or other conductors
- Recycling of modules and collecting high value components

By addressing these challenges and research needs, the module efficiency of silicon solar cells can be increased, and their LCOE reduced to, accelerate their deployment as well as helping to achieve up to 40 years of device operation warranty. Also, bifacial silicon PV can boost power production by up to 20%. All of these improvements will contribute to an increase in the overall power generation from PV. To capture these opportunities, the following requirements have been identified.

Specific requirements identified to support further development of crystalline silicon are:

- Improved accelerated operational lifetime testing
- Building up a pipeline of skilled researchers focussed on photovoltaic materials
- In order to test new structures/processing methods for silicon only, dedicated UK-based cell processing laboratory facilities that have capabilities at industrial level are needed
- Availability of specialist metrology equipment for PV materials (e.g. microwave photoconductance, sunsV_{oc})

Table 1: Topic Roadmap for Silicon

Silicon
Where are we now? State of art Crystalline silicon solar cells account for c. 94.5% of the market and global production is >150 GW_p. Average module cost was US$0.24/ Wp (end of 2018). The world record efficiency is 26.7% (Kaneka) for a laboratory test cell. Traditional aluminium back surface field (Al-BSF) technology has been displaced by passivated emitter rear contact cells (PERC). There are two main commercial wafer types (monocrystalline and multicrystalline) and until recently both have had significant market shares, but monocrystalline PERC is expected to dominate in the short term. Good quality commercial cells are typically 22-24% (monocrystalline) or 18-20% (multicrystalline), although there are significant outliers. Silicon heterojunction cells (SHCs) have a small market share, but are used as the base cells of perovskite-silicon tandems. More advanced cell structures such as interdigitated back contact (IBC) are available, but are not mainstream. Today's modules are extremely reliable and are typically shipped with 25-30 year power warranties. Bifacial cells that collect light from both front and rear surfaces boost electricity production from PV panels by 4-20% depending on climate and ground conditions, and manufacture of these products has been enabled by the availability of low-cost high-quality wafers. **Scope** All aspects of crystalline silicon solar cells (materials, surfaces/ interfaces, cell fabrication, manufacturing). 1. Silicon materials and cell architectures for bifacial solar cells. 2. Silicon materials and cell architectures for tandem solar cells. 3. The junction between silicon and other parts of a tandem cell. Out of scope are: 1. Non-silicon materials for silicon-containing tandems (covered elsewhere in roadmap) 2. Issues common to all photovoltaic technologies (glass, casing, inverters etc). **Desired future. What success would look like. What are the key performance characteristics / parameters?** The published ITRPV Roadmap (https://itrpv.vdma.org/) gives an excellent overview of the likely desired future, including detailed performance parameter forecasts from panels of international academics and industrial experts. Success would clearly include increases in commercial module efficiency, reductions in manufacturing and material costs, improvements in reliability, ultimately leading to further reductions in the LCOE. The market share of bifacial cells is forecast to grow substantially. The ultimate sign of success would be a large increase in the proportion of power generated by silicon PV, playing a key role in achieving climate change mitigation targets. Crystalline silicon is for utility scale and rooftop installations, so flexibility and transparency are not generally required features. Durability is already excellent, but increased reliability is expected with 40 years guarantees not an unrealistic prospect in the long term provided suitable methods for accelerated operational lifetime testing can be developed.

	Short term (next five years)	Medium term (five to ten years)	Long term (more than ten years)
Relevant research challenges	1. Stable carrier lifetimes including by reduction/ elimination of light-induced degradation (LID) and light and elevated temperature induced degradation (LeTID). 2. Extending the operational lifetime of silicon modules beyond the current 25-30 years by elimination of long-term operational degradation issues (*e.g.* potential induced degradation). 3. Ultra-high carrier lifetime substrates for rear-contact and bifacial silicon solar cells. 4. Improved surface performance for thinner wafers and bifacial devices including better surface passivation and improved light absorption (*e.g.* black silicon). 5. Improved materials for carrier selective contacts. 6. Development of lower temperature cell processes to reduce thermal budget while maintaining efficiency/ carrier lifetime. 7. Processes for improved production yield of thinner wafers (*e.g.* improved sawing and handling technologies). 8. New cell architectures that increase rear/front bifaciality towards 100% to enable novel vertical north-south panel orientation that extends daily electricity generation period.	1. Low-temperature silicon cell architectures (possibly dopant-free with thin film passivating contacts and low temperature metallisation). 2. Mainstream (*e.g.* PERC) and high efficiency (*e.g.* SHC, IBC) silicon technologies compatible with tandem architectures (*e.g.* perovskite-Si tandems). 3. Replacement of silver as an electrode material (*e.g.* by copper). 4. Recycling of relatively low efficiency end-of-life silicon PV modules (including those installed in the UK). 5. Integrated energy storage in silicon solar modules (*i.e.* batteries + PV in the same module).	Long term challenges are difficult to predict, but some ideas include: 1. Efficient and scalable interfacial charge transport nanolayers for silicon based tandem cells. 2. Possible kerfless manufacturing processes (to reduce material lost during sawing). 3. Large scale, commercially viable integration with other PV (*e.g.* in tandem devices) and energy storage technologies.

R&D required	1. Fundamental research into the mechanisms of bulk defect formation and elimination in the context of state-of-the art PERC processing. 2. Development of *p*-type substrates with dopants other than boron (*e.g.* gallium). 3. Development of low cost and industrially scalable processes for surface treatments of thinner wafers (*e.g.* improved texturing, surface passivation, impurity gettering, better light trapping). 4. Development of improved cell processing technologies for *n*-type silicon substrates (*e.g.* alternatives/ improvements to BBr_3 diffusions), including for bifacial cells. 5. Development of novel methods for materials and device characterisation (*e.g.* temporary passivation schemes, ways of measuring carrier lifetime in complete cells, improved accelerated operational lifetime testing).	1. Low-temperature formation of efficient passivating contact materials. 2. Development of new films that enable perovskites to be grown on Si PERC solar cells (*e.g.* avoiding amorphous silicon layers). 3. Fabricate of perovskite-PERC silicon tandem cells (in collaboration with the perovskite community). 4. Processing methods for electrode materials other than silver, while minimising contamination of the substrates. 5. Development of ways to recycle end-of-life modules efficiently while recovering high value components (*e.g.* silver).	1. Understanding the physical properties of nanoscale thin-film materials. 2. Fundamental research into new manufacturing methods (*e.g.* rolling, epitaxial silicon, lift-off technologies).
Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	1. Stable and dedicated funding stream for silicon PV materials/ devices, including funding for PDRAs. 2. Funding for UK PhD students (*e.g.* a Centre for Doctoral Training) and funding for talented international PhD students from which we receive many enquiries but are rarely able to support. These PhD programmes could involve visits/internships at the new processing and metrology facilities to accelerate the uptake of these new national resources within the UK PV community 3. Dedicated UK-based cell processing laboratory facilities for silicon PV (clear additional value for tandem community). 4. Availability of specialist metrology equipment for silicon PV materials and cells (*e.g.* photoluminescence lifetime imaging, microwave photoconductance decay, photoconductance	As for short term, plus: 1. Additional facilities for research and development to enable the scale-up of new silicon-based tandem structures. 2. Techno-economic analysis regarding cost-risk associated with validity of operational lifetime testing.	As for medium term.

	lifetime measurements, Suns V_{oc} etc). Staff and technicians are also needed to maintain and operate the equipment, as well as to perform training and establish protocols for use 5. Funding for strategic international collaboration with world-leading institutions (*e.g.* Fraunhofer ISE in Germany, UNSW/ANU in Australia) perhaps including the establishment of a joint international centre. 6. Acknowledgement of importance of working with international industry. UK manufacturing industry is currently minimal, but a key objective is to foster UK industrial growth in this sector. Silicon photovoltaics are essential to the UK's future electricity generation strategy and hence, in the short-term, schemes to work with international industry are vital.		
Metrics (performance requirements) for this materials system / device design concept, which will be **required for commercialisation**	Silicon PV is already a > $100bn industry, and small improvements to technology can have huge global impact. Relevant metrics exist at the sub-cell level (*e.g.* bulk carrier lifetime, surface recombination velocity, J_o, reflectance, absorption coefficient etc), at the cell level (*e.g.* V_{oc}, J_{sc}, fill factor, efficiency), and at the manufacturing level (*e.g.* polysilicon utilisation per wafer, silver usage per wafer). Key metrics are compiled elsewhere (*e.g.* ITRPV annual roadmap report, Fraunhofer ISE Photovoltaics Report at https://www.ise.fraunhofer.de/en/renewable-energy-data.html). Ideas arising from UK universities are likely to be developed in collaboration with industry, as the capital investment required to make commercial devices is considerable.	As for short term plus an in-depth analysis of costs savings and energy gains resulting in predicted $/W, LCOE, energy pay-back, and CO_2 off-set.	As for medium term.

<table>
<tr><td>Scale up and expected deployment rate (%)</td><td>The Compound Annual Growth Rate (CAGR) of PV installations was 36.8% between year 2010 to 2018 (Fraunhofer ISE Photovoltaics Report, November 2019). This is expected to continue, or accelerate, over the short to medium term. An estimate by Needleman et al. (Energy and Environmental Science, 9 2122-2129 2016) suggests that cumulative PV installed capacity needs to reach 7-10 TW by 2030 to have a reasonable chance of reducing carbon emissions from power generation sufficient to keep global temperature rises to below 2 °C, and silicon PV is the only viable technology on this timescale.</td><td>See predictions in ITRPV Roadmap.</td><td>Various scenarios are modelled in the ITRPV Roadmap. Their "electricity scenario" predicts an installed capacity of 22 TW peak in 2050 with PV generating 38 PWh (69% of global electricity production in 2050). Most of this will be from silicon-based PV.</td></tr>
<tr><td colspan="4">Technology issues that will determine the deployment
The technology is already being deployed in vast quantities. In the medium-to-long term there could be an issue with the availability of silver for contacts, but research into other contact materials should overcome this. Issues in the development of other PV technologies could hold back silicon tandem progress. Cost of glass could be a bottleneck for the roll-out of silicon bifacial technologies. Intermittency of solar generation necessitates rapid start-up alterative generators as deployment increases in countries where peak load does not match peak generation (currently pumped hydro and gas turbines, but could be batteries in the future although adds to the overall LCOE).

Non-technology issues that will determine the deployment
The availability of capital investment to build new factories. International political issues, including the degree to which governments engage with the need to limit climate change and the degree to which competing non-fossil fuel technologies are deployed (e.g. nuclear). For the UK, future international trade deals after Brexit could affect supply of PV materials and systems. Economics in countries outside the UK (e.g. China) in which the majority of solar modules are currently made. Financing of industrial scale solar installations is now the biggest single cost due to high interest rates on a "novel unproven" technology. Confidence in accelerated operational lifetime testing is key. The effects of global pandemics which could be both a threat to PV (reductions in manufacturing and destabilisation of global economies) but also possible benefits of PV in such an environment, e.g. the resilience of PV farms to continue to output energy under a lockdown compared to traditional power stations that require more day-to-day human involvement to keep them running.</td></tr>
</table>

THIN FILM CADMIUM TELLURIDE

CdSeTe/CdTe has the potential to become a leading thin film technology for low capital-intensity solar cells. The current champion cell efficiency is 22.1% (deployed module efficiency is 19%), and it is predicted that 25% cell efficiency could be achieved by 2025. CdTe PV is already the lowest cost technology ($0.20/Wp). Production from thin film CdSeTe/CdTe is at 6 GW per annum with plans to expand to 8 GW by 2022. It has a 5.5% market share and is currently the most important new thin film technology, being much less energy intensive than silicon with half the carbon footprint (15.83 – 20.11 gCO_2-eq./kWh[24]). Increasing the efficiency further still would make the technology compelling over crystalline silicon. The UK already has significant involvement in the development of CdSeTe/CdTe with NSG-Pilkington suppling the glass, fluorine-doped tin oxide transparent conductor, and buffer layer, which represent 50% of the cost.

In order to capture the opportunities from this technology, further research and development is needed to overcome the different technology-agnostic and commercial challenges. For instance, further research on coatings is needed to develop durable and low-cost anti-reflection cover glass for solar modules, and soiling of solar cells by birds and debris can also be seen to drive research on super-hydrophobic coatings. Coatings for the cover glass can help to increase IR reflection in order to reduce module temperatures and thereby increase the lifetime of the modules, and carrier lifetimes can be improved through Group V doping of the active layers of the solar cells. Improved surface passivation, and a better understanding of defect states and passivation strategies are another important areas which must be addressed. Improvement is also required on transparent conducting oxides (TCOs) to ensure stability and high band alignment of the layer above the TCO, and optical absorption by the cell itself needs to be reduced to improve the functionality of cadmium telluride-based solar cells.

Further development is needed to increase single-junction cell efficiencies to 25%, and to progress the development of bifacial and tandem devices to 32% efficiency, in order for cadmium telluride-based cells to achieve an uptake at the levels required for the UK to support a suite of PV solutions for a range of different energy needs and environments.
In order to support the research and development of CdTe-based solar cell technology, the following requirements have been identified. Firstly, funding is required for continued innovative research programmes by the established and internationally-competitive teams at Swansea (CSER), Liverpool and Loughborough. Also, access to world-class testing facilities for improvement of stability and durability performance of CdTe structures will be needed. Industrial partnerships with key industrial players in CdTe technologies such as NSG-Pilkington (UK), First Solar Inc. (US), and research partnerships with NREL and leading US universities must be forged and maintained. This will be necessary to carry out basic research, laboratory demonstrations of new concepts, development of facilities for testing and scale-up processes, and full techno-economic analysis of large-scale manufacturing. In the future, support will be required for the development and usage of in-line deposition tools for process development, modelling of tandem architectures, and ultra-thin glass in volume manufacturing.

Specific requirements identified to support further development of CdSeTe/CdTe are:

- Need internationally-competitive research teams that feature a high level of collaboration with industry and research training organisations
- Testing facilities for stability and durability, and facilities for industrial scale-up
- Partnerships with world leaders, including First Solar, NREL etc.
- Techno-economic analysis of large-scale manufacturing

[24] Mariska de Wild-Scholten, Energy payback time and carbon footprint of commercial photovoltaic systems December 2013 Solar Energy Materials and Solar Cells 119:296-305, DOI: 10.1016/j.solmat.2013.08.037

Table 2: Topic Roadmap for Thin Film CdSeTe/CdTe

Thin Film CdSeTe/CdTe

Where are we now? State of art.

Production of Thin film CdTe is at 6GW per annum with plans to expand to 8GW by 2022. It has 5% market share and is the most important new thin film technology.

Scope

- Application level: Utility scale and rooftop
- Increased Efficiency
- Lower manufacturing costs
- Improved durability

Desired future. What success would look like. What are the key performance characteristics / parameters?

CdTe PV is already the lowest cost technology ($0.24/Wp). Much less energy intensive than Si with half the carbon footprint. Increased efficiency would make the technology compelling over c-Si. UK involvement is already significant since NSG Pilkington supply the glass/FTO/buffer representing 50% of the cost.

	Short term (2025)	**Medium term (2030)**	**Long term (2050)**
Relevant research challenges	Increase cell efficiency to 25%	Introduce bi-facial CdTe	Tandem cells based on all CdTe alloys
R&D required	a) Group V doping (As, P) to increase carrier lifetimes and Voc. Activation currently 1% and needs to be 10% b) Improved met-oxide buffer layer above the FTO contact. Improved surface passivation. High transparency and good band alignment to CdSeTe	Development of suitable transparent conductor for back surface with electron reflector properties to allow thinner absorber layer.	- CdZnTe high band gap for top cell. CdSeTe/CdTe low band gap cell. - Advantage of continuous, low cost thin film manufacturing
Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	a) Funding required for internationally competitive teams at Swansea (CSER), Liverpool and Loughborough. b) Access to world class testing facilities for stability and durability. c) Industrial partnership with NSG-Pilkington (UK) and First Solar Inc (US) d) Research partnerships with NREL and leading US Universities	- Work with NSG Pilkington and First Solar in an academic/industrial partnership. - Work with NREL, Colorado State, Arizona State and South Florida Universities - Fundamental theory on defect states and passivation strategies	- In line deposition tools for process development, modelling of tandem architectures, ultra-thin glass in volume manufacture. - Academic/Industrial partnerships to carry out basic research, laboratory demonstration of new concepts, facilities to scale processes and full

			techno-economic analysis of large-scale manufacture
If relevant, the relevant metrics (performance requirements) for this materials system / device design concept, which will be required for commercialisation	- Already commercialised. First Solar (US), CTF Solar(China) Advanced Solar Power (China) - Electricity from Utility scale at <$0.02/kWhr - Module cost driven below $0.20/Wp	- Module efficiency at 25% - Enhanced energy yield for utility scale PV by 25%	Module efficiency 32%
If relevant, scale up and expected deployment rate (%)	Current increase in deployment is about 30% pa	- Depends on keeping competitive with Si - c-Si and tandem c-Si	PV market has increased at 35% pa compound for past 15 years. This is likely to continue.
Technology issues that will determine the deployment Thin Film CdTe is a 'second generation' technology with scope to achieve even higher efficiency and lower cost.			
Non-technology issues that will determine the deployment CdTe and Si are unlikely to be challenged at utility scale because the capital cost barrier to entry is too high ($1bn). Unlike Chinese Si manufacturers, First Solar is US based and receives no subsidies. NSG-Pilkington is its exclusive supplier of glass substrates.			

SINGLE-JUNCTION PEROVSKITES

Single-junction perovskites enable efficient devices that can be used to address a range of UK energy challenges e.g. BIPV, indoor PV and utility scale PV. Perovskites can be used for high efficiency solar modules with low capital intensity and low energy inputs. Thus, in future they can be integrated with other technologies, such as for solar fuel generation, producing ammonia, and solar water-splitting.

Currently, devices on rigid substrates have achieved 25.2% power conversion efficiency[25]. Flexible substrates achieve 17% to 18% power conversion efficiency. It is expected that rigid substrates will be largely deployed in the short-term, whereas flexible substrates with more demanding stability requirements are likely to be scaled up in the medium term. Commercialisation at scale will require better materials characteristics, especially stability, improved aesthetics and transparency as well as higher cell efficiency.

The scope of this topic includes different material systems for the components of the perovskite solar cell architecture, e.g. contacts, contact layers, interface passivation layers, and encapsulation. Due to the environmental impact, the scope also includes the development of lead-free alternatives and materials for lead capture.

One of the obvious research challenges is that perovskite solar cells are not as stable as silicon cells, and solar module lifetimes are currently short. Manufacturing at scale, LCOE, efficiency, and sustainability are further areas identified that require more research. Therefore, R&D is required on the passivation of perovskite films and improving their stability against environmental and operational degradation (with a strong focus on the fundamental science and characterisation required to achieve this), as well as improving module engineering (with a view towards low-cost and sustainable scale-up). Large-scale manufacturing technologies are required to be developed using inexpensive raw materials and sustainable processing methods (e.g. non-toxic solvents). Also, research should focus on optimum module design, and achieving high efficiency in large-scale modules.

The UK has a strong research community in understanding fundamental processes in perovskites solar cells, and in the manufacturing of modules. But more effort is needed in bridging the gap between basic science and scale-up and commercialisation, and this will require dedicated funding routes that reward and encourage such efforts. To aid further development of materials, test facilities for modules as well as facilities for pilots to strengthen TRL3 and TRL4 must be established. Furthermore, for sustainable development, a Doctoral training in photovoltaics and solar technologies is vital to build a pipeline of talent and skills in the UK.

Specific requirements identified to support development of single-junction perovskites are:

- Development of large-scale manufacturing technologies using inexpensive raw materials and sustainable processing routes (e.g. non-toxic solvents)
- Doctoral training in photovoltaics is needed to build up the UK pipeline of skills
- UK test facilities for a range of perovskite-based solar modules
- Pilot facilities in UK needed to strengthen TRLs 3 and 4[26]

[25] https://www.nrel.gov/pv/cell-efficiency.html
[26] As defined in reference 4

Table 3: Topic Roadmap for Single junction perovskite (Flexible Substrate (FS), Rigid Substrate (RS))

<table>
<tr><td colspan="4">Single junction perovskite (flexible, rigid and/or semi-transparent)</td></tr>
<tr><td colspan="4">Where are we now? State of art
Rigid substrates - high performing in Lab scale 25.2% power conversion efficiency; Lifetime >1000hrs in ambient conditions, as well as in 85% relative humidity and 85 °C temperature (damp-heat testing)
Flexible substrates - 17-18 % power conversion efficiency;

Scope
- Contact layers, Carbon & organic materials
- Metal Oxide charge transport layers
- Mixed cations materials; 2D/3D Hybrids
- Materials for increased surface passivation
- Inorganic perovskites
- Encapsulation
- Manufacturing strategy
- Lead-free & Lead-capture
- Green processing solvents (non-toxic)
- Transparent conducting oxides (TCOs)
- Ambient Processing
- Making modules
- Transparent contacts
- Interdigitated Back Contact Devices

Out of scope (commercial perspective): $MAPbI_3$, PEDOT:PSS; ITO; Indium/Gold; Spin-coating; Glove-box type fabrication; Vacuum Processing;

Desired future. What success would look like. Key performance characteristics / parameters

Stability; Efficiency; Scalability; Modularity; Low Energy Inputs; Low capital cost for manufacturing; Form Factor; Bending, Bend Radius; Nano-mechanical stability; Aesthetics; Transparency;</td></tr>
<tr><td></td><td>Short term</td><td>Medium term</td><td>Long term</td></tr>
<tr><td>Relevant research challenges</td><td>Passivation; Intrinsic Stability; Module Design; Efficiency; Scale-up of rigid substrate devices</td><td>Scale-up of flexible substrate devices; 3D Substrate; Generating Solar Fuel; Generating Ammonia; Lead-free device; Solar Water Splitting;</td><td>Generating Solar Fuel; Generating Ammonia; Solar Water Splitting;</td></tr>
</table>

R&D required The research and development path towards the desired future and the key milestones	**Where are we now? State of art** Research into the fundamental processes in lead-halide perovskites; Degradation Processes; Material Chemistry and Synthesis; Defect chemistry; Transient Spectroscopy; Optical Spectroscopy; Scale-up; Ab-Initio Theory; with in-depth synchrotron measurements (e.g., at Diamond Light Source); RAY Scattering; Making Modules with rigid substrates	Large area manufacturing; In-Situ Metrology; Advanced Microscopy methods - Nano Focus X-Rays; Chemical Mapping; Electron Modelling; Catalysis; Intelligent Material Design; Making Modules on flexible substrates; Laser Processing; Super Capacitors; Low-cost encapsulation	Catalysis; Lab Prototype - Scaling up for water splitting; integration of a perovskite solar cell and battery into one device (e.g., a photo-battery);
Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	**What are the other key enablers necessary to achieve potential** Large scale ALD to grow Al2O3 passivation layers for PERC; Adhesion Layer Coating borrowed from other fields; CDT; See Solar Commission Document on Future of Solar; SuperGen Funding; EPSRC Grand Challenges; Test Facilities for Perovskites modules in the UK	Bridge gap between research and manufacture; Strengthening commercialising labs/centres; Fundamental research required in TRL3/4; Building more pilot facilities in the UK for fabrication; large area solar centre facilities; Material synthesis scale-up labs; Coordination b/w Funding agencies;	Super-capacitors; batteries; Catalytic Capabilities (Chemical Engineering); Cross-Sector integration;
Metrics (performance requirements) for this materials system / device design concept that will be required for commercialisation	Stability last 10 years ; Commercial viability; Module Efficiency 15%	Module Efficiency 20%; Driving down cost;	Driving down cost: LCOE and the overall £/kWh of the solar cell that includes everything (e.g.: overheads etc.)

PEROVSKITE-SILICON TANDEMS AND OTHER PEROVSKITE MULTIJUNCTIONS

Multi-junction technologies (perovskite-silicon and all-thin film tandem cells without silicon) will have near-term impact, and they have a high potential for terrestrial utility scale and rooftop applications. However, there is a need to develop from perovskite-silicon tandems towards all-thin film tandems, which have the potential for lower capital intensity, which will be important for faster scale-up and manufacturing. Perovskite-silicon and all-thin film tandem cells both contain two heterojunctions, but there should also be efforts to develop triple-junction devices because they can achieve significantly higher efficiencies again. Triple-junction devices exist today comprise materials such as III-V semiconductors, which are very expensive, such that efficiency benefits currently outweigh their costs due to their increased complexity. However, the recent success of thin film perovskite devices has changed the commercial landscape in this area, and could help to drive research into low-cost, low LCOE triple-junction devices being achieved in the future.

There are approximately 20 commercial entities that work on perovskites in the UK, but fewer of them are using silicon-perovskite tandem solar cells. Oxford PV has a technology to deposit wide bandgap perovskite on silicon with 28% energy conversion efficiency when grown on silicon at wafer scale. This concept is mature (being at TRL7 to TRL8) and a manufacturing line on track for completion in the first quarter 2021. The reluctance of the PV industry to take up new technology exists owing to the high start-up costs in the UK, and therefore more incentives are needed to help new solar technologies to enter the UK market so that they can scale-up competitively with other global markets.

There is potential for the UK to achieve 50% peak solar electricity generation capacity in 2030[27] by increasing silicon solar cell deployment in which perovskite tandems can contribute a significant share. To realise this vision, 35% efficient perovskite-silicon tandem modules with 40-year lifetimes and £4/MWh LCOE are needed in order for sufficient and rapid uptake into the market to occur. These performance metrics will allow a shorter device lifetime to be tolerable if module replacement schemes (including refurbishments and recycling) for thin film tandems, which can still maintain low LCOEs, are implemented.

Research challenges for perovskite tandems are similar to other PV technologies described above, for instance, development of stable conductors and other contacts in these devices that can be scaled up to create a viable product relatively quickly. Some silicon-specific research challenges are also relevant for perovskites tandems, and ongoing innovations in the silicon solar cell industry, where electrochemical and engineering processes are mature and well-understood, can be applied to perovskite technology too, allowing long-term stable, lightweight perovskite-perovskite and other all-thin film tandems to gain in market share.

Owing to the high start-up costs for new materials technologies, sustainability requirements are generally important for ensuring efficient scale-up. Development of sustainable and inexpensive transparent conducting oxides and other contacts is needed across the PV field. In addition, silver and gold contacts need to be replaced with relatively low-cost materials, e.g., copper or carbon. Particularly in the case of perovskite tandems, reduction in the lead content in the active region of the device, and the related lead management system (i.e. lead scavenging) throughout the solar

[27] https://www.solar-trade.org.uk/uk-solar-peak-generation-record-broken-amid-fall-in-pollution-levels/

cell's lifetime is still a challenge. Therefore, a future strategy for a circular economy related to PV manufacturing should be developed, which will require methods to retrieve high-value materials from recycled devices. Large-scale manufacturing of perovskite solar cells requires reductions in the capital intensity, however this is a new market where competitive industry-scale production facilities may be viable in the UK. The UK lacks industry-scale production facilities for silicon, and it is likely that tailoring of silicon bottom cells will remain overseas in large silicon PV facilities in the short- to medium-term. Nevertheless, investment in building a domestic silicon manufacturing industry focussing on perovskite-silicon tandem development will further support growth of this new market.

Specific requirements identified to support development of perovskites silicon tandems and other perovskite multi-junctions are:

- Support the development of a circular economy strategy for PV manufacturing to address recycling of perovskite-based modules (particularly lead scavenging)
- Life cycle and techno-economic analyses for PV manufacturing
- Advanced characterisation equipment to understand operation and degradation pathways from the atomic level to the module level. This also applies to single-junction devices and other emerging materials in this field
- Silicon manufacturing line to demonstrate new silicon-based tandems

Table 4: Topic Roadmap for Perovskite Si tandem and Perovskite multijunction

Perovskite Si tandem and Perovskite multijunction
Where are we now? State of art - Around 20 commercial entities working on perovskites, but fewer on Si-perovskite tandems. Oxford PV have a technology to deposit wide-band-gap perovskites on Si. - 26% efficiency of two-terminal perovskite-silicon tandems with wafer size, with 20 mA cm^{-2} current density - TRL. 7-8 - Manufacturing of perovskite-silicon tandems by first quarter 2021 - *p-i-n* or *n-i-p* structured perovskite devices on heterojunction Si solar cell - No large tests yet; small tests passed industry standards for reliability - Market targets: Rooftop, terrestrial utility. Reluctance of PV industry to take up new technology. It's a financial mkt. **Scope** - Opportunities for new applications on other Si technologies. - Other Tandem opportunities (Perovskite-Perovskite, Perovskite-CIGS). - For rooftop or utility for large scale power generation. (Other niche apps, but not focus here). - Perovskite-CIGS including thin-film tandems to encompass other materials **Desired future. What success would look like. Key performance characteristics / parameters** - Energy equivalent of 2000 one gigawatt-scale factories is required to meet world energy demands mostly by solar. That includes large base of Si PV manufacturing until 2050 and beyond. PV still has a significant learning curve and can improve efficiency further. - PVs have the potential to product up to 50% of all electrical generation capacity in the UK by 2030 - Energy Security for UK is important, and it is important that we can make our own solar cells to fulfil our own renewable energy requirements - PV with LCOE ~£4/MWh, Power density ~350W/m2 is required to achieve this - Lifetime, 40 years; though module replacement schemes may be viable leading to shorter lifetime requirements. - Refurbishment; Recycling of rare elements are vital to ensure net-zero - Q: How fast can we build $bn factories? Depends on largely on Chinese manufacturing capabilities as China dominates this. These goals are ambitious, but are what needed for net-zero, and what could be made possible with new materials innovations.

	Short term **2020-2025**	**Medium term** **2025-2030**	**Long term** **2030-2050**
Relevant research challenges (see Appendix V)	- T-RTE 01, 5, 7, 8, 11, 13, 15 - Stable Si consistent with Perovskite processing conditions. - Making thinner Si for Per and general adoption of systems. - Develop sustainable manufacturing routes (solution and vapour)	T-RTE10, 17, 18, 22, 23, 24 - Lowering CAPEX of manufacturing plants. - Bifacial application specifically in commercial markets. - Green Solvents. Replacement for DMF and other polar solvents. - Developing Per-Per, Per-CIGS, including lightweight	- Having a position in Perovskite-Perovskite, Perovskite-CIGS including lightweight - Alternative thin film tandems or tandem layers - Triple junction variations including silicon and/or thin films (perovskite, CIGS, inorganic etc.)
R&D required Research and development path towards the desired future and the key milestones	- Narrow band gap for Perovskite development. - Reduced Pb alternative for top cell - Pb "scavenging" or managing components - Research into contact layers	- Sustainable and inexpensive transparent electrodes for Tandem	
Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	- Si cell wafer recovery is low value: silver and glass potential value - Fund policy for energy storage and generation - Prototype testing facilities across different technologies	- Si Manufacturing demonstration line for test devices	
Metrics (performance requirements) for this materials system / device design concept which will be required for commercialisation?	- Low toxicity of raw materials. Investment in UK manufacturing for products built under circular economy principles including dealing with Pb		- New transparent electrodes for tandems. Sheet resistance < 30ohm/sq.; - Transmittance as high as possible
Technology issues that will determine the deployment			

Techno-economic LCA of systems: UK industrial development system is just not there
Non-technology issues that will determine the deployment How to enable the UK PV glass supply chain. Policy to incentivise energy storage and home generation and building generation.

ALL MATERIALS APPLICABLE FOR BIPV

Building-integrated PV (BIPV) can be used as roof-tiles, windows and façades in industrial/agricultural buildings, greenhouses or in automotive applications. BIPV is a well-established research field; its potential for providing a pathway to significant decarbonisation in the building sector has been recognised for decades, and has been showcased in a variety of demonstrators. BIPV involves deposition of a solar cell structure and contracts onto building material, or a transparent solar cell onto irregularly-shaped or curved glass, depending on applications. However, BIPV is currently not cost-effective, and a large amount of R&D is still needed to make BIPV economically attractive.

The commercial breakthrough of BIPV depends on several critical parameters: power conversion efficiency (PCE) of the solar cell part of the installation, the average visible transmittance of light through window glass when coated with PV layers, structural colour of the building material or window glass once it has been coated, the weight of the window, roof tile etc. on addition of PV layers, and conformability with the window-frame or other building setting. Promising results under lab conditions and in demonstrators have been shown (e.g. Chen et al, 2012[28])), but prediction of the possible amount of electricity that could be generated autonomously by a building is currently still not reliable due to issues with BIPV device stability and durability, due to the fact that transparent layers tend to be made of organic materials which degrade quickly under processing conditions. The performance of BIPV is also reliant on the effects of environmental changes e.g. dirt landing on the surface obscuring light, damage to surfaces via cleaning etc. Another issue is a lower system performance at elevated temperatures, typical of windows and other surfaces on buildings and cars when illuminated by sunlight[29]. Because of the above performance and durability challenges with BIPV materials, alternative routes to deployment in the short-term will need to be investigated e.g. system modules that can be easily replaced, rather than designing cells to last for the lifetime of a building. Insufficient efficiency to provide the required electricity for the building may be compensated though additional functionalities such as heat management and insulation in the building walls, to ensure sustainability of the building until the technology develops further.

Research efforts are needed to increase transparency of the BIPV substrate in the near infrared region, as well as to increase transparency of the whole device. The overall aesthetic appearance of the modules, safety of various materials such as adhesive reliability and lamination strength are also important factors to be considered for scale-up, especially for very large heavy windows in buildings. Environmental sustainability, recyclability of components, and replacement of rare and toxic materials, are all important considerations for BIPV in the medium term.

Scale-up and module manufacturing will demand advances in the development of low-cost and reliable processes with low energy utilisation, in order to reduce the energy payback time. A major challenge is the safe transportation of BIPV systems to building sites, and there is an opportunity to engage with the construction industry to perform market acceptance studies of BIPV systems. EU regulations in large buildings necessitates solar and BIPV as the way forward. However, a detailed regulatory framework is essential, e.g. carbon neutrality and safety of the building, in order to provide an operational framework for industry, and to encourage commercial development. Regulation currently only focuses on new buildings, and does not apply to retrofitted buildings with

[28] Chen, K. S., Salinas, J. F., Yip, H. L., Huo, L., Hou, J., & Jen, A. K. Y. (2012). Semi-transparent polymer solar cells with 6% PCE, 25% average visible transmittance and a color rendering index close to 100 for power generating window applications. *Energy & Environmental Science*, *5*(11), 9551-9557.
[29] Maturi, L., Belluardo, G., Moser, D., & Del Buono, M. (2014). BiPV system performance and efficiency drops: overview on PV module temperature conditions of different module types. *Energy Procedia*, *48*, 1311-1319.

BIPV, however this may also require regulation in the long-term. It is expected that regulatory requirements will evolve over the short- and medium-term, and in the long-term BIPV will be the default option for all buildings.

Further enablers for early-stage development of BIPV include modelling, techno-economic analysis and life cycle analysis. Overall financial support of low-TRL R&D, academic-industry partnerships, and schemes for knowledge transfer are needed for advancing the BIPV field.

Specific requirements identified to support development of BIPV are:

- Scale-up facilities for testing large-area installations e.g. strength of adhesives and lamination, in order to ensure reliability and safety of BIPV used in building cladding
- Life cycle analysis of PV materials needed to ensure sustainable low-toxicity materials
- Regulation that buildings need to be carbon neutral in order to encourage update to >10% of new-builds

Table 5: Topic Roadmap for All Materials for BIPV

All materials that could be used for BIPV
Where are we now? State of art - The main parameters today are appearance, cost and efficiency in this priority order - There is an efficiency and cost penalty for roof tiles in comparison to building-added Si panels. The roof design currently costs $42,000 for a 2,000 sq foot roof with a 10 kW capacity and a warrantee of 25 years. This is 3 times the price of Si panels (numbers from Tesla Solar). - Safety is important (for various materials such as adhesive, lamination etc.) and in line with regulations - There are two important parameters; the power conversion efficiency (PCE) multiplied by the average visible transmittance and this should be greater than 3% **Scope** - Applications: Roof-tiles, windows, facades, car porches, street furniture, industrial and agricultural buildings, green houses, automotive Properties: transparency, semi-transparency, uniformity, neutral colours, grey (super important). Structural colour (refractive) is ok for facades and currently available. Thermochromic, electrochromic colour changing glazing. Weight and conformability. - Module manufacturing in scale, ability to make non-standard sizes, ability to make it local to the building site. - Monolithic designs, alternative patterning designs, very highly conductive and transparent substrates **Desired future. What success would look like. Key performance characteristics / parameters** - The ambition would be to minimise losses in comparison to a system optimised purely for energy conversion. A system that could have a lower efficiency perhaps, but could offset this with additional functionality e.g. air purification. Fundamentally, it will have to affect the performance of the building throughout its whole lifetime and make the building CO_2 neutral from cradle to grave - It has to look nice. The main parameters for the future are expected to be are appearance, and lifetime of the system. - The system will need to last for the lifetime of a building or be easily replaceable. - The system should not have a negative impact with the environment (thermal management) of the building. - Safety is important (for various materials such as adhesive, lamination etc.) and in line with regulations - Sustainability and availability or required resources and materials - using materials of high crustal abundance. There are two important parameters for power conversion efficiency (PCE) multiplied by the average visible transmittance and this should be greater than 10%

	Short term	Medium term	Long term
Relevant research challenges (see Appendix V)	T3-RTE1, 2, 3, 5, 7, 8, 9 T-RTE-4, 8, 16, 17, 18, 19, 20, 21, 24, 25, 26		
R&D required The research and development path towards the desired future and the key milestones	- Transparency for the whole device - 70% but it is pixelated (uniform sheet that is laser ablated) - Transparency of the substrate in the near infrared is also a current challenge as well as charge selective contacts - Device stability to be good enough to be able to predict power output - Understand how environmental changes affect the device performance (e.g. dirt, cleaning etc.) - Low cost and reliable, non-energy intensive processing of materials to reduce energy payback time - Reducing toxicity	- Transparency for the whole device - between 80-90% optical spectrum in the visible without pixilation - Device stability up to the lifetime of the building - Changing the appearance without affecting the efficiency - Low cost and reliable, non-energy intensive processing of materials including lightweight and non-glass substrates - Recycling of everything - Eliminating toxicity	
Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	- Cable system management, but needs to be addressed for commercialisation - All these things are required: finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis - Regulation is critical - having a zero CO2 target for buildings is important. Also have the building regulations specify required targets for safety - The construction industry needs to be brought along - Market acceptance studies to verify if people will accept these systems		
Metrics (performance requirements) for this materials system / device design concept that will be required for commercialisation	- The metrics (cost, efficiency, appearance, energy pay back, lifecycle analysis) needs to improve to achieve scale		

Scale up and expected deployment rate (%)	- Less that 1% - mainly demonstrators	- Because of EU regulations in large building solar and BIPV is the only way forward. This regulation currently does not apply to retrofit only to new buildings. - Potentially more than 10% of new buildings will have adopted this technology. By 2035 it will be a default choice for new buildings	- By 2050 it will be a default choice for new buildings - 100% will be adopting BIPV

MOBILE ENERGY SOURCES – STANDALONE PV

Standalone PV is important for indoor applications or for autonomous small devices (e.g. Internet of Things). The innovation area is gradually emerging and the development of new materials is currently at a low TRL. However, the potential for establishing new markets for standalone PV is limitless.

This topic focusses on organic photovoltaics materials (OPV), dye-sensitised solar cells and emerging inorganic materials, with a band gap 2 eV for optimised use under indoor lighting. The current state-of-the-art is 24% power conversion efficiency for organic PV, 34% for dye-sensitised solar cells, and 35% for lead-halide perovskite solar cells[30]. Investigations into different inorganic materials with a focus on indoor applications has begun, such as bismuth oxyiodide, BiOI, and caesium antimony iodide, $Cs_3Sb_2I_9$, but this research is at an early stage. Solar cells based on amorphous silicon is the predominant current indoor PV technology, but this has around 10% efficiency under indoor lighting (6uW/cm^2 at 200 lux[31]).

The most important enabler to accelerate deployment of indoor PV modules is the establishment of industry standards. Unlike measurements of solar cells for outdoor applications, there are no standards widely used for indoor PV (e.g. no standard spectra, no standard specifications of the spacing between the light source and device when assessing efficiency and power, no standards for stability measurements etc.).

While the limit for the theoretical solar cell efficiency is >50% for most PV materials with a 2 eV bandgap, current technologies are far from approaching this limit. Currently, the driving force for development of indoor PV applications is improving the power conversion achievable by the module, which must be sufficient for the specific application to work effectively, rather than focusing on the conversion efficiency of the module. After these two critical factors, materials costs, module stability to degradation, non-toxicity of components, and manufacturability will be the most critical parameters. However, in the short-term, the maximum power conversion for the envisioned functionality will be the main performance metric for this early-stage technology.

As calculators powered by integrated amorphous silicon solar cells became popular technology in the 1970s and 1980s, the development of standalone PV for indoor applications can be accelerated by initial market uptake as an integrated device segment as part of another application. Academic-industry partnerships will therefore be key for the development of this area, as there is currently no specific indoor PV market. It is vital to identify partners and engage with engineers, architects, and consumer goods specialists. Furthermore, it is important to understand user needs and aesthetics, and perform market research to identify early markets that can facilitate the improvements and developments. Henceforth, co-development with engineers from different fields for electrical integration is critical. The PV component should be compatible with digital manufacturing, so it can be produced as a joint component to provide power within an integrated sensor or IoT device or piece of hardware. Any newly-emerging standalone PV materials system needs to be better than amorphous silicon in terms of its electrical performance, stability, ease of manufacturing, recyclability etc.

[30] Wang, Y., Qian, D., Cui, Y., Zhang, H., Hou, J., Vandewal, K., ... & Gao, F. (2018). Optical gaps of organic solar cells as a reference for comparing voltage losses. *Advanced Energy Materials*, *8*(28), 1801352.
[31] Mathews, I., Kantareddy, S. N., Buonassisi, T., & Peters, I. M. (2019). Technology and market perspective for indoor photovoltaic cells. *Joule*, *3*(6), 1415-1426.

Specific requirements identified to support development of standalone PV are:

- Encourage research into recyclability and resource stability of all technology products
- Support standardisation of device performance measurement under indoor lighting
- Facilitate engagement with engineers, architects, consumer goods specialists, and market research to understand user needs and aesthetics

Table 6: Topic Roadmap for Mobile Energy Source – Standalone PV

Mobile Energy Source - Standalone PV
Where are we now? State of art Single junction values (all performance parameters are measured under indoor lighting): OPV Indoor = 24% (note no standard measurement at the moment) Indoor dye cells = 34% Indoor Dye-cells scaled = 34% - Classes of materials relevant for standalone applications - For indoor lighting perovskites that are 35% efficiency under indoor lighting[32] - Different inorganic materials that have started being investigated for indoor applications such as BiOI, Cs3Sb2I9 - a-Si is one of the dominant indoor PV technologies, but has 10% efficiency under indoor lighting[33] **Scope** Indoor application specific: - Low frequency indoor - Modulated response - High linearity and high efficiency at low intensities - Stability of absorber itself will be quite important - requires thinner encapsulation - Appropriate stability standards - Adjunct materials that work with PV materials themselves for energy harvesting - Optical device designs to improve light collection, amplifications, direction etc. - Toxicity and relevant regulation - Appropriate stability standards and testing needs to be developed for indoor PV, as well as standardised ways to measure performance **Out of scope:** - Large modules **Desired future. What success would look like. Key performance characteristics / parameters** - Cost, toxicity etc. maybe more important than power conversion efficiency provided the latter is sufficient

[32] DOI: 10.1002/aenm.201801509
[33] DOI: 10.1016/j.joule.2019.03.026)

- Durability target of 5 years - Defining a common performance target(s) that is universal is very important - a-Si is currently used for most indoor applications - we should use as targets for these materials - currently amorphous silicon performance is 6 uW/cm2 @200 lux - Flexibility for certain indoor applications - All technologies can be recycled - 50% materials to be recycled by weight/ using sustainable materials - OPVs can be slightly stretched - positive for Aerospace applications			
	Short term	**Medium term**	**Long term**
Relevant research challenges (see Appendix V)	- T3-RTE3 - T3-RTE12, T3-RTE14, T3-RTE17, T3-RTE18 - Identify more specific indoor specific TCEs and top contacts - cost, stability, non-toxicity and sheet resistance (in this priority order) will be the most critical parameters for indoor PV materials - 5cm x 5cm monolithic area - Materials development for transport materials - more diversity - Encapsulation - water & vapour transmission of 10 to the minus 6 - Physical junction thickness > 500nm dry layer (only a few materials currently work at this thickness) - this would enable high volume printing processes - Flexibility of design to allow variety of bespoke products of different sizes and shapes - Toxicity of solvents - Indoor cells - operational stability - Reproducibility - Standardise measurements	- Set up an independent testing lab to conduct these measurements - Simpler manufacturing - Digital manufacturing compatible	

R&D required Research and development path towards the desired future and key milestones	- Pathway for junction thickness: - Non-fullerenes 500nm - Morphology optimisation across the z plane – Morphology control - TCE need to be sufficient and manufactured in cost-effective ways for small batches - Solid state transport materials and/or electrolytes for dye cells stability and efficiency is important. - Investigating different optical structures that are required to improve light management into the cell. Also understanding if these boost performance mechanisms do not introduce light loss pathways - Operational stability to ensure that the devices work even after dark storage, fatigue strength and mechanical stability (fracture toughness) - Diversify appearance e.g. different colours, patterns etc. - Non-chlorinated solvents or green manufacturing for chlorinated solvents	- Non-chlorinated solvents or green manufacturing for chlorinated solvents: - New photo-absorbers that are easier to process - New materials that enable digital manufacturing	
Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	- Better partnerships with other fields - engineering - Work with electronic engineers because these devices can work in both high and low light conditions. New electronics are required. - Recycling is important especially from the encapsulation and substrates - Indoor - engagement with architects especially making statement pieces - Engage with consumer good marketing specialists to gauge interest in potential indoor applications - Close links with the printing and coating industry - Accelerated test methods - Standard test facilities and testing protocols		
Metrics (performance requirements) for this materials system / device design concept which will be required for commercialisation	- a-Si performance as targets for these materials - currently amorphous silicon performance is 6 uW/cm2 @200 lux - Also all other aspects of a-Si performance such as stability, manufacturability etc.		
Technology issues that will determine the deployment Focus on sustainability of materials - huge advantage for OPV and Dye-cells			

Non-technology issues that will determine the deployment - For indoor - no current standard - require defined standard for the future - It will be important, if there was a key application that provides an entry to the market (like calculators did for a-Si) - HRI may want to act as a conduit between different companies to network different partners and use its network to connect people in this space - HRI could be looking for market opportunities in this domain to guide companies

MOBILE ENERGY SOURCES – TERRESTRIAL AND SPACE MOBILE

Mobile PV is in demand for applications in autonomous vehicles, aerospace applications, telecommunications and satellite technologies. New materials for these applications can be deposited on flexible substrates which have high integration potential with automotive technologies, satellites and other autonomous applications requiring high power densities. Current lab efficiency of multi-junction solar cells is 47% (with solar concentrator) and 29.1% for single-junction cells. The industry standard level for a commercial solar cell for space applications is 30% at beginning-of-life conditions (BOL) for AM0[34] (Aho et al. 2017[35]) and power density of 0.5kW/kg for multi-junction cells on non-flexible substrates. For triple-junction solar cells on flexible substrates, efficiencies around 29% measured with spectral conditions at AM0 1.0 , and power densities of 2kW/kg are the current standard. The efficiencies of single-junction perovskites and tandem perovskites are around 25.2%.

Within the scope of this topic there are different characteristics that define the functionalities required for mobile applications, such as high linear response over total irradiance, high efficiency at low intensities, and bespoke spectral response depending on intended usage. Reliability is defined by the duty lifecycle of the specific application, e.g. 10-year satellite mission or unmanned aerial vehicle (UAV) mission for 60-100 days. The main envisioned target for the future of such technologies is to achieve device lifetimes that match the intended application lifetime, or duration of the mission. Power densities for new technologies need to be at least 2kW/kg, but achieved at lower costs than those technologies in use today e.g. through the development of inexpensive transparent conducting oxides to replace those currently used. However, the cost of the solar cells is not the most important factor for some mobile applications, since the uptake of new technologies in this area is ultimately determined by the lifetime of the application (e.g. mobile PV installed in a car) or by the duration of a mission, and the system-level costs are more important than the individual costs of the solar cells, which are often a small fraction of total costs (e.g. in satellites). Nevertheless, requirements for high power conversion efficiencies are certainly much higher compared to those required in utility-scale applications, currently just under 20 % e.g. automotive PV usually requires efficiencies above 20%, space applications require efficiencies over 30%.

An important requirement to accelerate deployment of mobile PV applications is the development of lightweight devices. Long-term challenges for space applications are to conduct future space missions to destinations that are not reachable today due to limitations in current PV performance. Reducing radiation damage to solar cells and delamination of layers is also a critical challenge in space applications. A fundamental understanding of radiation tolerance in solar cell materials must be developed, with devices that show high reliability over a defined duty cycle. Integration with energy storage is a major challenge in the development of some mobile PV applications e.g. integrated PV and energy storage is critical to the development of driverless cars.

Acceleration of R&D efforts requires multidisciplinary partnerships with other research fields (in particular computer science and engineering) to address cutting-edge research challenges related to systems-level integration of PV architectures. Integration at this level involves engaging with end-users of the technology, in particular for the automotive sector and space manufacturing industry, to understanding how PV can meet end-user needs early in the product development stage. Because

[34] Air mass coefficient = Zero describes the spectrum outside the atmosphere

[35] Aho, A., Isoaho, R., Tukiainen, A., Polojärvi, V., Raappana, M., Aho, T., & Guina, M. (2017). Performance of dilute nitride triple junction space solar cell grown by MBE. In *E3S Web of Conferences* (Vol. 16, p. 03008). EDP Sciences.

of the unique application characteristics in this field, academic-industry and related consortia built must be industry-specific, and not PV technology-specific.

Key requirements for mobile energy sources including terrestrial and space applications:

- Support of establishment of partnerships with other fields (in particular computer science and engineering)
- Radiation hardness testing for space applications
- Development of accelerated stability-testing protocols including those targeting flexible devices
- Engagement with end-user industries, e.g. satellite and automotive industry, to understand end-user needs and ensure integration of technologies from an early stage

Table 7: Mobile Energy Source – Terrestrial and space mobile

Mobile Energy Source - Terrestrial and space mobile
Where are we now? State of art Single junction values (all performance parameters are under AM1.5G, unless otherwise specified (i.e.: not under AM0 or indoor lighting): OPV Record lab cell = 18% Dye-cells = 12% OPV scaled (1cmsqd) = 14% Dye cells scaled = 10% OPV scaled mini-module = 8% (Heliatek) Lab efficiency (Multi Junction): 47%% (Concentration) Lab efficiency (Single Junction): 29.1% Standard level (Commercial Space Cell) : 30% BOL AM0 ; 0.5KW/Kg (Multi-junction non-flex substrate) Triple Junction Flexible= 29% AM 1.0 ; 2KW/Kg Single-Junction Perovskites = 25.2%; Mini-modules SJP = 18% Tandems Perovskites CIGS = 26% Perovskites-Perovskites = 25% **Scope** - High linearity - High efficiency at low intensities - Bespoke spectral response - Radiation tolerance - Broad temperature range - Mechanically robustness - High power and energy density

- Flexible form factor
- Cost factors
- Storage compatibility; joint power
- Reliability/Defined Duty Cycle (for critical application)

Out of scope:

- Wafer based Silicon
- Thick heavy glass

Desired future. What success would look like. Key performance characteristics / parameters

OPV lab cell = 22% (within 2 years)
OPV scaled mini-module target = 15% (within 5 years)

Dye cells = 20% in next 5 years

- All technologies can be recycled - 50% materials to be recycled by weight/ using sustainable materials
- Positive temperature derating could be harnessed
- OPVs can be slightly stretched - positive for Aerospace applications
- Radiation hardness for space applications?
- Power density target for new technologies including perovskites = 2KW/Kg (at lower cost < $5/Watt)
- Reduction in cost through tech development in other fields/areas (Telecomm and Photonics)
- Lifetime targets (Space) = 10 years, (UAV) = 60-100days
- Cost important, system cost outweigh cell cost (e.g. Satellite)

	Short term 2025	Medium term 2025-2035	Long term 2035 and above
Relevant research challenges	**T3-RTE3 - T3-RTE12, T3-RTE14, T3-RTE17, T3-RTE18** **T-RTE-10, T-RTE-17, T-RTE-18, T-RTE-22** **Perovskites and Organics:** **-** TCE sheet resistance - 1ohm/sq with AVT above 88% - 5cm x 5cm monolithic area - Materials development for transport materials - more diversity - Encapsulation - water & vapour transmission of 10 to the minus 6 - Physical junction thickness > 500nm dry layer (only a few materials currently work at this thickness) - this would enable high volume printing processes - Reproducibility of Solvents and Junction Materials - Toxicity of Solvents and Junction Materials **Others:** **-** Creating lightweight silicon - Lightweight and affordable III-V	**T-RTE-15, T-RTE-16, T-RTE-59**	- Mars mission relevant : Radiation critical; - Jupiter Mission relevant: Radiation critical; - Driverless cars: Power density - Battery/storage challenges
R&D required The research and development path towards the desired future and the key milestones	**Perovskites and Organics:** - Pathway for junction thickness: - Non-fullerenes >15% 500nm - Morphology optimisation across the z plane - TCE: embedded grid on AlZO - Solid state transport materials based on co-ordination polymers. - Electrolytes for stability/ efficiency - Morphology control **Others:** - Radiation tolerance - Silicon lift-off - III-V Lift-off and EPI development - Lift-off and substrate reuse 8" (Large area)	- Non-chlorinated solvents or green manufacturing for chlorinated solvents	

Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**	**Other key enablers necessary to achieve potential:** - Better partnerships with other fields - computer science and engineering - Bulk commodities minerals industries entering this space - manufacturing and recycling - Computer/ HMI development - Close links with the printing and coating industry - Accelerated test methods - End-user interaction : engagement with satellite catapult, automotive industry to understand the end-user needs etc. - Consortium : Industry specific (Automotive, Satellite, Mission specific, etc.)		
Metrics (performance requirements) for this materials system / device design concept that will be required for commercialisation	**Efficiency** Space: 30%+ Automotive: >20%; **Cost** Space: 20 US$/W, specifically for III-V 3 US$/cm^2 Automotive: 5 US$/W **Radiation Tolerance** for Space: 10 years **Specific Power** Space: 2kW/kg Automotive: 2kW/kg		
Technology issues that will determine the deployment: Focus on sustainability of materials - huge advantage for OPV and Dye-cells			
Non-technology issues that will determine the deployment: Si PV Europe Electronics legislation/ CdTe legislation - recycling			

MATERIALS CHALLENGES ACROSS TECHNOLOGIES

This section summarises the analysis across all topic roadmaps, in order to highlight the challenges faced by the existing PV industry, and challenges in scaling of emerging PV.

CHALLENGES IN THE EXISTING PV INDUSTRY

This topic explored materials challenges across existing commercial PV technologies. It must be noted that many of the identified challenges are common to both existing PV and emerging PV technologies.

The drive towards decarbonisation of the UK's energy systems has created commercial opportunities for numerous PV application fields, for example the International Technology Roadmap for Photovoltaics (ITRPV) forecasts that bifacial solar cell modules will have a 60% global market share by 2029. In order for the UK to take advantage of this, the challenge of implementing appropriate time-of-day metering must be addressed, as the power generated will vary considerably depending on the angle of the incident sunlight throughout the day. Similarly, emerging PV applications such as BIPV and Floating PV systems on lakes and reservoirs have also been predicted to increase in demand, however numerous industry challenges must be overcome in the UK for rapid uptake e.g. BIPV in the UK currently does not have the advanced testing procedures necessary for handling as a building material, optimisation of thermal management, safety requirements, and for structural resistance over the building's lifetime.

A major challenge for industry is that there are a variety of mechanisms for degradation of solar cell components over the module lifetime. These are:

- Acceleration of solar cell degradation by high module temperatures
- Degradation of the backsheet, the outermost layer of the PV module, over time
- Water ingress into modules due to insufficient encapsulation
- Vulnerability of the anti-reflective coatings on solar cells to high temperature and humidity

Another major issue in PV manufacture is Potential-Induced Degradation (PID), which affects crystalline silicon PV modules that are not grounded, resulting in current leakage to the ground, which over time can result in performance losses of up to 30%[36]. Although PID-free module designs are available, PID affects about 20% of modules in the UK due to a humid and rainy climate which accelerates current leakage. Power degradation due to thermal cycling, humidity, freeze-thaw cycles and other environmental factors is a significant challenge. The precise mechanisms of such system-level degradation, and the development of new PV architectures to mitigate these, are required.

As well as improvements to the module components, there is a need for the development of materials that can reduce power losses in the solar cell electronics, such as in the inverters and bypass diodes. The main candidates for these are wide bandgap semiconductors, typically compound semiconductors, and the materials and manufacturing challenges in this area are at an early stage.

Soiling of the solar cell cover glass by dust, dirt and bird droppings is another major challenge in PV deployment. This reduces the power output by up to about 10% in the UK, and much more in dry

[36] http://files.sma.de/dl/7418/PID-PVOBox-TI-de-11.pdf

and dusty countries. Reduction of soiling can dramatically improve the power output, and a strong focus on development of super-hydrophobic coatings to reduce soiling, or to make surfaces easier to clean, is vital to improving solar cell power outputs.

Module heating in silicon-based PV and perovskite PV through IR radiation from the sun is an important challenge, because the photocurrent drops with temperature. The development of materials or products that reduce either the operating temperature of the module, or the negative temperature coefficient of the solar cell material, such that current flows at high rates regardless of solar heating.

The UK has three main areas of expertise in PV: (1) fundamental research, (2) manufacturing, and (3) on-field operations (e.g. by solar asset managers). However, national-level collaborations are needed to facilitate knowledge transfer between these three areas of expertise to enhance R&D sufficiently to increase the UK's competitive position worldwide. A major factor in preventing knowledge transfer between these three areas is that the UK lacks purposeful testing infrastructure across all TRLs. State-of-the-art environmental testing facilities are required to provide the appropriate equipment and infrastructure for the low-TRL development of materials, coatings and cover glass, and to improve environmental stability of emerging PV technologies. Standardisation testing kits and processes are not currently available for any of the above early-stage materials development, nor for PV technologies at higher TRLs. For instance, there is also a need to develop low-cost methods of rapidly assessing the health of large solar fields. Certification testing is currently concentrated in a few large companies, so future testing centres would be ideally located at academic institutions to ensure broad UK usage, however the site location must be considered carefully to overcome logistical challenges for in-field testing. A transition towards new business models in "fab-less" materials manufacture and testing, that are more service-oriented and less dependent on capital expenditures, will allow the industry to benefit from input technologies that can integrate with PV e.g. Internet of Things and Big Data. Development of these new types of business models requires knowledge transfer through national initiatives in order to explore the breadth of possible UK markets, including engagement with universities and the public sector.

Key requirements across all existing PV topics:

- Central facilities for high-level environmental testing with outdoor testing capabilities
- Standardised test procedures for modules, especially at higher TRL levels
- Support for SMEs and catapult for commercialisation
- Increase the number of trained people in the field (CDTs)
- Consortia bringing together academia, industry, asset managers and Innovate UK together

Table 8: Topic roadmap for R& to overcome material challenges for existing PV industry

<table>
<tr><td colspan="4">Material challenges for the existing PV industry

1. Causes and mitigation of Potential Induced Degradation (affects about 20% of modules in the UK); System level challenges based on product architecture especially power degradation. There has been good progress on this for new systems, though existing systems still suffer from PID
2. Soiling of the cover glass. This reduces the power output by up to about 10% in the UK and much more in dry and dusty countries.
3. Affects of water ingress into modules/better encapsulation. Backsheet degradation in Solar PV.
4. Vulnerability of sol gel based anti-reflective coatings to temperature and humidity.
5. General materials degradation over the module lifetime, including the effects of module temperature on degradation.
6. Development of Low cost methods of rapid assessment of the health of large solar fields
7. Testing: Is there sufficient demand? - Gap in Environmental testing; Low TRL target required (R&D required for various TRL levels); EU definitions
8. Testing not available for certain standards; Lack of testing kits in high TRLs, Lack of soiling PV systems;
9: CAPEX --> OPEX Business model in testing; National initiatives, including Universities, public sector.
10. Certification Testing concentrated in few large companies;
11. Logistic challenges for testing in field testing - New testing centres required preferably in institutions, though other sites should also be considered.
12. Material for invertors especially High Voltage: Requirement for materials that can reduce power losses in invertors and bypass diodes. Main candidates are wide bandgap semiconductors, typically compound semiconductors. Significant manufacturing challenges when upscaling, therefore current costs are high.
13. Module heating in silicon based PV. Cause: IR radiation from the Sun. Perovskites also affected by this phenomenon. The challenge is to develop materials/products that reduce either the operating temperature or the negative temperature coefficient of the product.
14. BIPV need to perform as building material – requires optimisation of materials for thermal management and long term structural resistance.
15. Safety challenges, most notably in BIPV and perhaps some rooftop installations.
16. ITRPV forecast that bifacial modules will have 60% market share by 2029. There will be challenges (and benefits) for deployment in UK. Time-of-day metering would be benefit to deployment of this technology in UK.
17. Floating PV systems (on lakes and reservoirs) are anticipated, but will have important material challenges.</td></tr>
<tr><td></td><td>Short term - until 2025</td><td>Medium term - 2025 - 2030</td><td>Long term - until 2050</td></tr>
<tr><td>R&D required R&D advances to overcome challenges and weaknesses</td><td>-Understanding the mechanisms of problems in soiling and degradation and PID for coating
-Understanding adhesion especially for glass
-Surface chemistry
-Standardised test procedures for modules
-Data quantification</td><td>-Understanding adhesion especially for glass
-Coating and testing at module scale
-Field-trials
-Design principles
-Optimisation
-Accelerated tests to Field trials
-Standardised test procedures for modules
-Testing protocols for glass testing</td><td>-Fix the PID challenge at material level</td></tr>
</table>

Required competences, resources (finance, people, knowledge, partnerships, modelling, techno-economic analysis, life cycle analysis), **enabling technologies and other enablers**		-Consortiums (academic, industry, asset managers; Innovate UK type) -Asset management expertise -Funding for TRL 4 -Investment in testing -Local expertise -National level ROADMAP and Prioritisation -Government intervention required	-Catapult -Support for Innovative SMEs -To increase number of people (PhDs)	
Requirements that would benefit the UK PV community and PV deployment	Testing requirements	-Central lab capable for high level environmental testing with outdoor testing capabilities -Prototyping and field trials -Development of protocols	-Central lab capable for high level environmental testing with outdoor testing capabilities -Collaboration/ Consortium approach with international bodies -New deployment concepts	-New testing requirements for new materials
	New deployment concepts of current technology	-BIPV degradation -Non contact temperature measurement for field modules -Correlation with EL techniques with other inspection Power measurement and other failures	-Integration with energy storage non-grid, Large Scale	
	Manufacturing	-Anti-soiling coating -Off Grid application potential Sub-Saharan Africa South East Asia - Power generation for vaccine systems etc. -Repurposing of high cost components	-UK strong in Glass side, exploit the leadership position -Manufacturing of the testing equipment - bring in partners in UK	

CHALLENGES IN SCALING EMERGING PV

This topic explored material challenges for emerging PV technologies. Some of the challenges are applicable across all materials systems and device design concepts, others are specific for a particular application. And, there are some overlaps with the challenges faced in deployment of existing technologies.

The main materials-related challenges relate to the different aspects of stability, for instance mechanical, environmental, thermal, light, partial shading, chemical, organic, appearance and the reliability of materials. It is also important to identify additional standard tests for the emerging materials (including both IEC accelerated testing and outdoor studies) to address certain degradation pathways. Application specific testing is needed for different product lifetimes.

Sustainability is an important research field regarding emerging PV. For instance, feasibility studies and identification of environmental aspects of extracting of raw materials for new technologies are required for assessment of scalability of actual materials. And consideration of environmental impacts should involve material availability, toxicity and recycling and end of life solutions. Henceforth, there is a need for a life-cycle analyses.

At the product level, and partly related to stability, better understanding of physical characteristics of the product and product performance e.g. electrical and degradation are topics to be addressed by the R&D. Scalability of the device efficiency for the representative product also needs also a deeper exploration, as for example some applications like IoT do not need to be scaled-up as they are already at the size of product. However, scale-up also requires a compatibility between material and manufacturing processes for the representative product.

Successful roll out of technology is obviously always related to costs. Capital and operating costs for the representative product need to be cost-competitive against incumbent technologies. Cost-competitiveness is dependent on consistency of performance when product is manufactured at scale and consistency of its performance over the lifetime.

Material R&D required is relatively general across all materials. Encapsulation is very important and edge-sealant will be useful for both, emerging and established PV. For metallisation academic labs use often gold or silver, consequently for scaling cheaper metals are needed at the cell level and interconnect level. Further R&D needed at material level is around:

- Identification of TCOs, e.g. ITO are might be not viable for scaling up
- Interface adhesives and preventing delamination of layers
- Optical management to crease efficiency across different technologies
- Anti-soling methods

At system level, R&D is needed on integration of materials inside cells and integration of cells into modules as well as on spectral response impact with tandem or multi-junction systems.
Related to manufacturing processes, an assessment and selection of realistic and cost-effective processes e.g. inkjet, spin spray, laser scribing etc. is needed to ensure the compatibility between materials and manufacturing scalability. Also, understanding of how change at one layer will impact other layers in a multilayer cell giving necessary insights for better layer alignment. Fast and high-

resolution spatial characterisation is important to support optimisation, upscaling and defect analysis.

To support the R&D activities described above digital twinning at the system level and comparison of system modelling with field performance will help to understand degradation pathways and performance at the module level. Electro-optical modelling at system level is needed as well as to understand hot-spots, shading and degradation.

A lot of manufacturing and tool development has been outsourced and there is a lack of equipment and expertise in the UK. Testing requirements are similar to the requirements for existing technologies, as specified in previous chapter. Particularly, for new materials, new specific stability tests need to be developed as well as field data is required for proving bankability. Cell and failure mechanisms will need to be fundamentally understood through advanced characterisation tools compatible with large cells or modules. Identifying of what is available in the UK for cells, components and modules, establishing of manufacturing prototyping facilities and tool development facilities will be of a strategic importance.

Key requirements for emerging PV:

- Improved models applicable to the system level to identify hot-spots, shading, degradation etc.
- More investment in labs capable of testing on the industrial scale; industrial fab facilities
- Standardised accelerated degradation tests developed for new technologies

Figure 5: Material challenges in scaling emerging PV

<table>
<tr><td colspan="5">Materials challenges in scaling emerging PV

1. Stability (mechanical, environmental, thermal, light, partial shading, chemical, organic, appearance etc) and /or reliability of materials (all layers)
2. Additional standard tests that may have to be identified for the emerging materials e.g. different degradation profiles (including both IES accelerated testing and outdoor studies). Also testing for different product lifetimes for application specific/appropriate tests.
3. Sustainability i.e. feasibility and environmental aspect of extracting raw materials, end of life solutions, material availability, toxicity, recycling, life-cycle analysis etc.
4. Understand
a) physical characteristics of the product and
b) product performance e.g. electrical, degradation etc.
5. Scalability of the device efficiency for the representative product.
6. Compatibility between material and manufacturing processes for the representative product
7. Capital and operating costs for the representative product and cost-competitive against incumbent technologies as appropriate.
a) Consistency of performance when product is manufactured at scale.
b) Consistency of product performance over its lifetime.
8. Application-specific performance requirements such as semi-transparency etc.</td></tr>
<tr><td colspan="2"></td><td>Short term - time?</td><td>MT</td><td>Long term</td></tr>
<tr><td rowspan="2">R&D required to overcome challenges and weaknesses</td><td>Material R&D</td><td>-Selection and development of encapsulation materials at cell level (transparency, refractive index, moisture permeability, thermal conductivity, stability and recyclability). Encapsulation for both for the cell and for the edge-sealants
-Cost-effective metallisation appropriate for interconnection, at the cell-level
-Developing TCOs especially if TCOs are deposited over the active layer
-Interface adhesives for different materials e.g. glass/plastic, interconnections between cells etc. to decrease delamination
-Optical management to increase efficiency.
-Anti-soiling methods
- Use of cheaper electrode materials, e.g. replacing Ag and Ag electrodes with carbon</td><td></td><td></td></tr>
<tr><td>System (cells and modules) R&D</td><td>-Integrating materials inside cells and integrating cells into modules
-Spectral response impact with tandem or multi-junction systems</td><td></td><td></td></tr>
</table>

	Other	- Manufacturing processes - assessment and selection of realistic and cost-effective processes e.g. inkjet, spin spray, laser scribing etc. - Compatibility between materials and manufacturing scalability - Feedback of layer alignment for multilayer cells - Fast and high resolution spatial characterisation to support optimisation, upscaling and defect analysis		
Required competences, resources, enabling technologies and other enablers		-Digital twinning at the system level: comparing system modelling with field performance -Electro-optical modelling at system level to understand hot-spots, shading, degradation etc. -Manufacturing skills for scale-up -Equipment design and development -Annual workshop to summarise progress and highlight priorities		
Requirements that would benefit the UK PV community and PV deployment	Testing requirements	- More investment in "measurement labs" with capacity for both measurement and analysis. This is particularly important for R&D. Provide flexibility for new/emerging technology testing e.g. CIGS. -Focus on exposure tests -Build a databank of accelerated performance (field data) -For outdoor exposure tests need to have a network of partners including European partners -Being more involved in material development teams so that material-specific tests could be developed.		-Need to be able to test large areas to enable module testing
	Manufacturing	-Having a manufacturing prototyping facility. This could be linked to tool and equipment development -Establish what is available in the UK (for cells, components and modules)		

CONCLUSIONS AND RECOMMENDATIONS

The national environmental and energy policy goals set a frame, in which solar energy generation becomes an important pillar. The analysis has shown that the highest potential of solar energy generation can be captured by having the strategic focus on both established technologies and emerging new materials and application concepts. The large-scale manufacturing and deployment of established technologies face challenges that demand further research and development. And the nature of discovery of new materials and applications is addressing challenges through continuing research and providing required resources. Nevertheless, commonalities and overlaps in requirements and needs were identified across material categories to capture the opportunities of the different PV technologies.

In particular, these requirements are:

- **Development of the stability and performance of the materials identified** above and specifically of sustainable and inexpensive transparent conducting oxides
- **Testing facilities,** standardised test procedures and equipment, and specifically:
    - Central facilities for accelerated degradation testing, along with a team of experts working to develop protocols for accelerated testing of new materials to demonstrate bankability. This should be a national resource available to all academic and industrial groups. The testing facilities should enable the measurement of environmental stability, testing outdoors, testing under damp-heat conditions, testing under concentrated illumination. In addition, these facilities should allow for the testing of the strength of adhesives and lamination to ensure the safety of the BIPV used in building cladding as well for labs capable of testing on the industrial scale, to scale-up processes and to strengthen TRL 3 and 4[37]
    - Standardised accelerated tests procedures, e.g. for degradation, stability, to measure device performance under indoor lighting needs to be set out and especially for test at higher TRL levels
    - Dedicated UK-based cell processing facilities for silicon and emerging PV materials that can be used to tailor silicon devices for novel applications, e.g., tandems with perovskites
    - Availability of specialist characterisation equipment for PV materials and devices for understanding operation mechanisms and degradation pathways, e.g. microwave photo-conductance, sunsV_{oc}, advanced microscopy and spectroscopy techniques
- **Life Cycle Analyses** of PV materials are needed to ensure sustainable manufacturing, low toxicity of the materials and precursors, with the aim of having technologies recyclable
- **Regulation** for buildings to be carbon neutral in order to encourage uptake of BIPV to >10% of new-builds
- **Manufacturing** and **large-scale manufacturing technologies** are already an active area of research and remain of high importance and therefore, need to be developed further, using inexpensive raw materials and sustainable processing routes, e.g. non-toxic solvents. An advantage is that the UK is leading in this research area and Pilkington being a world leader in TCO deposition
- Silicon manufacturing line is needed to demonstrate new tandems with silicon and other silicon developments
- For CdSeTe/CdTe a **techno-economic analysis** of large-scale manufacturing is required.
- **Opportunities for doctoral training** in energy materials and photovoltaics, as well as training schemes for postdoctoral researchers and workers in industry. These will be needed to build up

[37] Definition as specified above

UK's pipeline of skills and increase the number of **skilled researchers and trained people in the field**

- **Establishing new funding routs to encourage commercialisation** of technologies from lab-based research. An important enabler is also support for SMEs and catapult for commercialisation
- **Consortia** need to be established bringing academia, industry, asset managers and Innovate UK together. It will be essential to strengthen **partnerships** with national laboratories, including NREL and Fraunhofer ISE, but also to be in dialogue with world-leading manufacturers such as First Solar, Sunpreme and Pilkington, which is supplying all the glass substrates

APPENDICES

I. Participants
II. Workshop methodology
III. Workshop Agendas
IV. Challenges and enablers for all new PV materials
V. Specific challenges and enablers for established thin films and other established inorganic
VI. Specific challenges and enablers for perovskites and perovskite-inspired materials
VII. Specific challenges and enablers for organics and dye-sensitised solar cells
VIII. Specific challenges and enablers for emerging inorganic materials
IX. List of figures
X. List of tables

APPENDIX I: PARTICIPANTS

Materials roadmapping workshops were commissioned by the Henry Royce Institute and were delivered by IfM Education and Consultancy Services Limited.

WORKSHOP DETAILS

DATES

First Session: 30th March 2020, 14.00 – 16.00
Second Session: 3rd April 2020, 11.00 – 12.00
Third Session: 3rd April 2020, 15.30 – 17.30
Fourth Session: 24th April 2020, 13.00 – 15.00
Fifth Session: 27th April 2020, 13.00 – 15.00

FACILITATION

Dr Diana Khripko
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Brian Saunders	University of Manchester
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David Lidzey	University of Sheffield

David Scanlon	UCL
Elizabeth Gibson	Newcastle University
Fernando Castro	NPL
Iain Crowe	University of Manchester
Isobel Hogg	Institute of Physics
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Jenny Nelson	Imperial College of London
John Murphy	University of Warwick
Kenan Isbilir	Above Surveying
Lata Sahonta	Henri Royce Institute
Louise Hirst	University of Cambridge
Marina Freitag	Newcastle University
Martyn Rush	Polysolar
Matt Black	Solivus
Matthew Halsall	University of Manchester
Mike Walls	Loughborough University
Moritz Riede	University of Oxford
Neil Robertson	University of Edinburgh
Nicholas Grant	University of Warwick
Nigel Mason	PV Consulting Ltd
Nigel Mason (ex BP Solar)	PV consulting
Paul Bates	BIPV Co
Paul Laidler	Powerroll
Paul Meredith	Swansea
Peter Wilshaw	University of Oxford
Rachel Evans	University of Cambridge
Richard Curry	University of Manchester
Richard Friend	University of Cambridge
Rob Palgrave	UCL
Robert Hoye	Imperial College of London
Ross Hatton	University of Warwick
Sam Stranks	University of Cambridge
Sebastian Bonilla	University of Oxford
Sheetal Handa	BP
Stuart Boden	University of Southampton
Su Varma	NSG-Pilkington
Tasmiat Rahman	University of Southampton
Tom Betts	Loughborough University
Tony Peaker	University of Manchester
Trystan Watson	Swansea
Wendy Flavell	University of Manchester
Will Hitchcock	Above Surveying

Topic Roadmap Participants for Crystalline Silicon PV: John Murphy, Tony Peaker, Matthew Halsall, Iain Crowe, Peter Wilshaw, Sebastian Bonilla, Nicholas Grant, Stuart Boden, Tasmiat Rahman, Nigel Mason
Topic Roadmap Participants for Cadmium Telluride-based PV: Michael Walls (lead)
Topic Roadmap Participants for Single-Junction Perovskites: David Lidzey, Trystan Watson, Wendy Flavell, Alison Walker, Neil Robertson

Topic Roadmap Participants for Perovskite-Silicon Tandems and Other Perovskite Multi-junctions: John Major, Chris Case, Jenny Baker, Sam Stranks, Robert Hoye, Mike Walls

Topic Roadmap Participants for All Materials Applicable for BIPV: Brian Saunders, Libby Gibson, Martyn Rush, Neil Robertson, Mike Walls, Rachel Evans, Marina Freitag

Topic Roadmap Participants for Mobile Energy Sources – Standalone PV: Robert Hoye, Martyn Rush, Rachel Evans, David Lidzey, Neil Robertson

Topic Roadmap Participants for Mobile Energy Sources – Terrestrial and Space Mobile: Louise Hirst, Paul Meredith, Sam Stranks, Lata Sahonta, Brian Saunders, Neil Robertson

Topic Roadmap Participants for Challenges in the Existing PV Industry: Michael Walls, Alan Taylor, Fernando Castro, Kenan Isbilir, Lata Sahonta

Topic Roadmap Participants for Challenges in Scaling Emerging PV: Nigel Mason, Samuel Stranks, Robert Hoye, Su Varma, Brian Saunders, Chris Case, Tom Betts, Matt Black

APPENDIX II: WORKSHOP METHODOLOGY

The methodology adopted was based on wide-ranging engagement with research communities to define the roadmap objectives and expectations, to design and customise the strategic framework for the roadmapping; to develop questionnaires for the research communities involved, and to modify workshop process steps to ensure participation of the entire research community. The workshops brought together academic and industrial experts in the four respective technology areas, and involved both offline and online data collection phases. The offline phases were used for data collection from individual participants and publicly-available research sources, followed by data consolidation and, where necessary and appropriate, prioritisation. The online workshops were used for data review, analysis and deeper exploration of essential issues. The quality and reliability of the process was maintained by a Steering Committee involving roadmapping facilitators and technical leads from each of the four research communities.

In total, 26 workshops sessions were held across the four technology areas identified by Royce between March 2020 and June 2020. These revealed several materials sub-topics of particular interest for contribution towards the net-zero targets, as well as highlighting important fundamental research and commercial technology enablers that need to be established. These outputs significantly aided research communities' understanding of the future direction of energy materials research, towards the achievement UK's net-zero emission targets by 2050.

The roadmapping workshop methodology consisted of three parts: design, the workshops themselves, and reporting of the workshop outcomes.

DESIGN

During the design phase, the following activities took place:

- Discussing and designing in detail the workshop methodology and process. The workshop used the **S-Plan** framework developed by the IfM over a period of several years[38] [39] [40]. The framework has been configured to help universities and research organisations align their research activities with industry needs, supporting decision-making and action;
- Designing the templates necessary to support the workshop activities;
- Agreeing the detailed workshop agenda;

[38] http://www3.eng.cam.ac.uk/research_db/publications/rp108

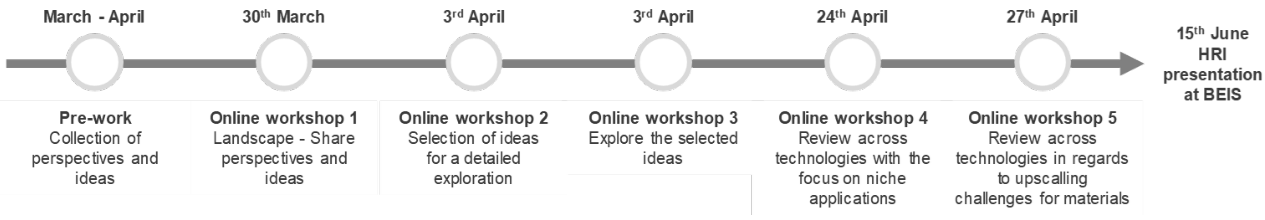
[39] Phaal, R., Farrukh, C.J.P., Probert, D.R. (2004). "Customizing Roadmapping", *Research Technology Management*, 47 (2), pp. 26–37.

[40] Phaal, R., Farrukh, C.J.P., Probert, D.R. (2007). "Strategic Roadmapping: A workshop-based approach for identifying and exploring innovation issues and opportunities", *Engineering Management Journal*, 19 (1), pp. 16–24.

- Agreeing the desired workshop outputs.

WORKSHOPS

The roadmapping workshop process for the stream *Future of the New Materials in PV systems* brought together participants from the research community and industry and had the following session plan:



The objectives of each session were as following:

Online workshop 1 “Landscape – Share perspectives and ideas”

- Review the material systems and device design concepts for the four PV material technology categories
- Review the research challenges, enabling technologies and other enablers
- Identify and fill in any gaps

Online workshop 2 “Selection of ideas for a detailed exploration”

- To select the new materials systems / device design concepts within each PV technology category for a detailed exploration in the workshop 3
- To set up the working groups that will be exploring each idea in the workshop 3

Online workshop 3 “Explore selected ideas”

- To explore selected material systems and device design concepts for PV systems
- To map the research and development path and required resources
- To describe the expected deployment and required technological and commercial enablers
- What are the topics that also need a deep dive?

Online workshop 4 “Review across technologies with the focus on niche applications”

- To review the topic roadmaps with the focus on Niche Applications
- To decide whether to do one overarching roadmap covering all niche applications or to split into small teams to add existing and / or explore additional topics

    a. BIPV
    b. Indoor PV
    c. Other niche applications (space, mobile PV) incl. new tandem technologies

Online workshop 5 “Review across technologies in regards to upscaling challenges for materials”

To capture:

1. Material challenges for the existing PV industry
    - How can new materials innovations help existing technologies?
2. Material challenges in scaling emerging PV
    - What would be required for commercialisation of emerging PV materials?

- What are the challenges that many academics working on the earlier TRL stages wouldn't foresee?

Finally, the IfM ECS transcribed all of the output from the workshop in electronic format, drafted the current report and distributed it to Royce for review and wider circulation.

APPENDIX III: WORKSHOP AGENDA

Session 1	
14.00–14.05	General welcoming
14.05–14.10	Welcome from HRI
14.10–14.20	Introductions, objectives and workshop process
14.20–14.30	Data provenance and review process
14.30–15.30	Review and identify gaps for materials systems & design concepts
15.30–15.50	Feedback review of the group work
15.50–16.00	Wrap-up and process feedback

Session 2	
11.00–11.10	Introductions, Objectives and Workshop process
11.10–11.30	Review the prioritisation results in groups
11.30–11.50	Set up the working groups for exploring the priority topics
11.50–11.55	Feedback of review discussion
11.55–12.00	Wrap-up and process feedback

Session 3	
15.30–15.40	Introductions, Objectives and Workshop process
15.40–17.00	Group discussion of key priorities
17.00–17.25	Presentation and review discussion
17.25–17.30	Wrap-up and process feedback

Session 4	
13.00–13.15	Introductions and Objectives
13.15–13.30	Recap and Group discussion
13.30–14.45	Topic roadmaps for material challenges
14.45–15.00	Presentation and Wrap-up

Session 5	
13.00–13.15	Introductions and Objectives
13.15–13.30	Summary of the topic roadmaps
13.30–14.45	Topic roadmaps for material challenges
14.45–15.00	Presentation and Wrap-up

APPENDIX IV: CHALLENGES AND ENABLERS FOR ALL NEW PV MATERIALS

ID	Research challenges, enabling technologies, other enablers
	New Material Exploration and Screening
T-RTE-1	SCV Theory (several complex variables theory), and machine learning for the purpose of mathematically modelling materials
T-RTE-2	Understanding of quantum mechanics involved in how new materials actually work, and whether or not there are new materials that can be massed produced cheaply
T-RTE-3	Explore new physics e.g. plasmonic systems
	Band gap
T-RTE-4	Addressing the band gap rule to attain high efficiency NIR conversion
T-RTE-5	A band gap of 2 eV is optimal for indoor photovoltaics, allowing self-powered autonomous small devices
T-RTE-6	The materials with a band gap close to 2 eV are ideal as photocathodes for water splitting. These need to be combined with wider band gap materials to enable self-powered artificial leaves for producing H2 and other fuels for cleaner production of long-chain hydrocarbons.
	Better match of spectral response to solar spectrum
T-RTE-7	Semiconductor photon detectors for the far infrared region of the spectrum and night vision - cheaper, better matched to the solar spectrum for increased efficiency, have a large area capability - ideally on a roll, Easier and less power consuming fabrication processes.
T-RTE-8	New materials that can utilise different parts of the spectrum and have linear responses to intensity extends their capabilities to low-light scenarios and opportunities where transparency
T-RTE-9	Finding semiconductors that divide up the spectrum in the optimal way
T-RTE-10	Solar Junction’s technology tackles the problem for the infrared end of the spectrum
T-RTE-11	Better match of spectral response to solar spectrum
T-RTE-12	Increasing the range of light that can be absorbed and transformed to electrical energy
	Properties: flexibility and low weight
T-RTE-13	Solar cells cheap, flexible (like what can be put in clothing)
T-RTE-14	Weaknesses of Si stem from the fact that it is an indirect band-gap semiconductor this necessitates (i) long minority carrier diffusion lengths and hence the high processing costs of inflexible crystalline material, (ii) layers thick enough to absorb the incident radiation. Thus the areas where new materials can compete are on processing cost, thickness/weight and flexibility.
T-RTE-15	Application in in low-light conditions (flexibility and weight)
T-RTE-16	Low weight
T-RTE-17	Flexible substrates including fabrics
	Property: Longevity, reliability, robustness, stability
T-RTE-18	High stability
T-RTE-19	Longevity
T-RTE-20	Reliability
T-RTE-21	Photocorrosion of components, understanding mechanism and treatments to improve stability.
T-RTE-22	Chemical complexity at all the device interfaces compared with Si; typically multiple materials used - control of interface chemistry and band-bending necessary, and this needs to stay stable for 10-15 year life of device
T-RTE-23	Other non-PV materials can be used to provide protection from degradation via atmospheric ingress in to PV systems; passivation from oxidation and moisture damage, reduction of UV light damage

T-RTE-24	Rigid and robust are not drawbacks of products which are expected to last 25 years. In addition, for rooftop or building integrated PV (BiPV), the PV modules have to match the lifetime of the roof or the building: even if flexible, high-efficiency products are available for free, the cost to replace them every two or three years is higher than the rooftop PV system itself. So new materials can only compete with existing technology if they can match the existing reliability, with comparable efficiencies.
	Property: earth abundance
T-RTE-25	Earth abundance
	Properties: toxicity, deposition, end of life, recycling
T-RTE-26	Circular economy for PV, recycling
T-RTE-27	Simpler deposition techniques
T-RTE-28	(Increase) Lifetime in the field, recycling
T-RTE-29	New materials need to be processed or deposit onto different type of substrates
T-RTE-30	Reduced toxicity of new materials
T-RTE-31	Avoiding toxic or rare materials
T-RTE-32	New combined electrode HTL/ETL allowing for only the PA layer to deposited
	Costs (materials, production, installation, integration etc.)
T-RTE-33	New materials need to match the lifetime of the application; they have to match the lifetime of the roof or the building: even if flexible, high-efficiency products are available for free, the cost to replace them every two or three years is higher than the rooftop PV system itself
T-RTE-34	Lower cost
T-RTE-35	Easy to be fabricated
T-RTE-36	Cost of materials
T-RTE-37	Costs of processing, production, manufacturing
T-RTE-38	Costs of installation
T-RTE-39	LCOE will require 1) reductions in transportation, balance of system costs, etc. or 2) increases in efficiency beyond the theoretical limit for Si.
T-RTE-40	Understanding of quantum mechanics involved in how new materials actually work, and whether or not there are new materials that can be massed produced cheaply
	Property: efficiency
T-RTE-41	Better performance / efficiency
T-RTE-42	High absorption co-efficiency
T-RTE-43	High quantum efficiency
T-RTE-44	In short, the only way a new technology will compete with crystalline silicon for rooftop and utility scale solar is through lower LOCE, which essentially means higher efficiency.
T-RTE-45	Higher efficiencies through better single junction cells or, more likely, tandem configurations. This may be with two novel absorbers, or a new absorber on top of silicon.
T-RTE-46	High efficiency PV device requires other materials with complementary properties to act as electrodes
	Reliability and testing service platforms
T-RTE-47	While it would be a significant step to develop a competitive technology, the UK is much stronger in the PV system R&D of the rest of the PV system parts. The UK has currently the largest companies and consultancies at a global level for PV system development, design, asset management, and O&M. This means that R&D in inspection, reliability of systems, etc, will also have high impact and significant benefits for the UK industry.
T-RTE-48	Characterisation platforms for large format devices which have high resolution and sensitivity.
T-RTE-49	Robust stability testing under appropriate conditions to prove the technology
	Application
T-RTE-50	For alternative applications such as computing, sensing, etc. to establish a market
T-RTE-51	New materials are more suitable for non-flat surfaces

T-RTE-52	Space power applications present a new opportunity that is only just being explored
T-RTE-53	Could PV ever be directly applied to 'rough' surfaces? This would require materials and devices to have a very high defect tolerance. To overcome limitations due to very rough surfaces, semiconductors would typically need to be made into 'thick' films (thicker than surface roughness). This would require the development of solution-processable materials that had very high charge-carrier mobility.
T-RTE-54	BIPV - IF these could be made as cheap as conventional building materials, and as durable as them in terms of their physical and chemical properties then they could be used instead of concrete
T-RTE-55	A 10% extension of the range of an EV through solar is a considerable achievement
T-RTE-56	Coupling the solar cells with more efficient batteries
T-RTE-57	Materials with near infra-red or UV absorption only, transmitting visible.
T-RTE-58	All of the emerging PV systems come from solution processing - which does open up new markets for small-scale personal applications to e.g. mobile phones and wearables, and curved surfaces, or could be sprayed over odd-shaped window surfaces (plans exist for this to happen on some quite large skyscrapers). These materials have an ease of production that also lends itself to small-scale micro-generation - for example in remote parts of the world/those with a high irradiance. Solar fuel approaches along these lines can (for example) be used to generate H2 or other fuels directly from the Sun's energy. Weight for weight, direct generation of solar fuel is much more efficient than solar PV + battery storage of the energy.
	Manufacturing, Design, Scalability
T-RTE-59	Non-planar surfaces (curves etc) - new methods of coating/treatments to allow for application on to non-flat surfaces - insulating metal surfaces with materials that can then be printed/coated/deposited with PV materials - car bodywork
T-RTE-60	Printing deposition with high quality inks
T-RTE-61	Ease of coating over large areas
T-RTE-62	Need to develop new processes for defect characterisation to improve manufacturing processes.
T-RTE-63	Scalability and production at low temperature
T-RTE-64	Ability to coat materials onto curved surfaces
T-RTE-65	Processable materials to be combined with non-traditional substrates in a low temperature process presents exciting opportunities
T-RTE-66	PV devices aesthetically attractive
T-RTE-67	New PV materials and technologies can be decentralised form Asia allowing for more regional or local manufacture
T-RTE-68	Quantum dot solids, and developments od dye-sensitised solar cells, and there has been rebooted recent interest in organic PV. One issue is preparing any of these systems in large enough quantities for large scale solar farms
T-RTE-69	Lower power consumption during manufacture of Czochralski growth of large silicon ingots requires high temperatures
T-RTE-70	Simple synthesis - low number of steps, high yield, repeatable
	Services, Installation and Integration
T-RTE-71	(Reduction of) installation issues
T-RTE-72	In the UK for quality control services, inspection services and leading the characterisation field is important, in order to minimise failure costs or transfer this costs back to manufacturers.
T-RTE-73	Present solid-state cells are suitable now for small systems to ~ 5 kW capacity on buildings
T-RTE-74	Power electronics for use in PV installations, wide band gap semiconductors such as GaN and SiC are appealing due to their power handling capabilities

APPENDIX V: SPECIFIC CHALLENGES AND ENABLERS FOR ESTABLISHED THIN FILMS AND OTHER ESTABLISHED INORGANIC SOLAR CELL SYSTEMS

ID	Research challenges, enabling technology, other enablers
T2-RTE01	Processing and scale up
T2-RTE02	Stability of materials
T2-RTE03	A manufacturing process for kerfless silicon wafers
T2-RTE04	Replacement of silver for contacts (e.g. with copper)
T2-RTE05	Integration of silicon into commercially viable tandem technologies (e.g. with perovskites)
T2-RTE06	Reducing wafer thickness
T2-RTE07	Reducing kerf losses
T2-RTE08	Large scale ALD to grow Al2O3 passivation layers for PERC
T2-RTE09	High cost but high performance PV materials that could be used in high-end electronic devices.
T2-RTE10	Efficiency: further work to increase power conversion efficiencies through device structure and new materials design
T2-RTE11	2 losses from solar cover glass – 1. Anti-reflection coating and 2. Anti-soiling – possibility with hydrophobic coatings?
T2-RTE12	Durable and low cost anti-reflection coatings for the cover glass
T2-RTE13	Super-hydrophobic coatings to reduce soiling (soiling reduces the power output by 10% in the UK to 50% in MENA counties).
T2-RTE14	Coatings for the cover glass to increase IR reflection to reduce module temperature
T2-RTE15	These would benefit from UK manufacturing opportunities
T2-RTE16	CdTe research challenges: Group V doping of the absorber to improve carrier lifetimes
T2-RTE17	CdTe research challenges: Optimisation of Se grading at te front of the cell.
T2-RTE18	CdTe research challenges: Development of a stable buffer layer above the TCO with good band alignment
T2-RTE19	CdTe research challenges: Improved TCO's. Reduced optical absorbtion.
T2-RTE20	CdTe research challenges: Current champion cell efficiency is 22.1% (module efficiency is 19%); 25% cell efficiency possible by 2025.
T2-RTE21	CdTe research challenges: Tandem CdTe based solar cells with band gaps engineered by alloying.

APPENDIX VI: SPECIFIC CHALLENGES AND ENABLERS FOR PEROVSKITES AND PEROVSKITE-INSPIRED MATERIALS

ID	Research challenges, enabling technology, other enablers
T1-RTE01	Built in capture system for Pb in event of failure and water ingress
T1-RTE02	Achieve neutral colour semitransparent perovskite solar cells in large scale R2R production
T1-RTE03	Direct generation of solar fuel
T1-RTE04	Direct generation of NH3
T1-RTE05	Stabilising current materials and contacts promising for tandems
T1-RTE06	Developing new lead-free absorbers that are efficient and stable
T1-RTE07	Directed funding for exploratory materials and interface exploration/validation
T1-RTE08	Productivity enhancements of tandem cell production
T1-RTE09	Elimination of lead compounds in perovskite
T1-RTE10	Replacement of silver with copper metallisation
T1-RTE11	Achieving 25-year stability with perovskite modules
T1-RTE12	Stable band gaps ~2 eV in perovskites
T1-RTE13	Stable, long lifetime low band gap perovskites for perovskite-perovskite tandems
T1-RTE14	In Relation to T1-10: Semi-transparent perovskite solar cells (Note Colour issues need sorting)
T1-RTE15	Perovksite devices offer high efficiency and there is a lot of work being done on stability, but results from this work seem quite contradictory, non-reproducible, and very specific to particular device stacks. A particular challenge to making progress in this area is the need for robust protocols for device lifetime studies under highly controlled conditions and with statistically meaningful sample sizes.
T1-RTE16	Hybrid Si perovskites - sprayable and can be ink-jet printed
T1-RTE17	Hybrid Si perovskites - low energy input costs
T1-RTE18	perovskites, increasing stability is a major challenge, together with development of low cost encapsulation techniques.
T1-RTE19	Perovskites - Reducing the toxicity of the materials (i.e. lead, tin) and the solvents used to process materials is also a concern.
T1-RTE20	lead-halide perovskites face several challenges. Firstly is the instability of the material itself (it will degrade in air within a month and will dissolve in water).
T1-RTE21	Secondly, the lead content in the perovskites is an important limitation, and public perceptions of deploying a lead-based technology may be a limiting factor. Identifying lead-free alternatives will be critical
T1-RTE22	Perovskites - can the system be sealed in an economic manner such that the stability in air issue is negated but the materials can be easily recycled, thus minimising lead transfer to
T1-RTE23	Properties: Flexible, lightweight, transparent, conductive substrates with low series/charge-transfer resistance for flexible devices (Avoiding ITO).
T1-RTE24	Developing transparent p-type conductive oxides for tandem cells

APPENDIX VII: SPECIFIC CHALLENGES AND ENABLERS FOR ORGANICS AND DYE-SENSITISED SOLAR CELLS

ID	Research challenges, enabling technology, other enablers
T3-RTE1	new patterning and deposition methods (low temp)
T3-RTE2	non-flat surfaces and non-plastic/glass surfaces
T3-RTE3	transparent bus bars
T3-RTE4	Morphology Control in Blended Heterojunctions
T3-RTE5	Low Sheet Resistance, Low Cost TCE
T3-RTE6	Stability AM1.5 and AM1.0
T3-RTE7	Production equipment
T3-RTE8	Inexpensive flexible encapsulation
T3-RTE9	Recycling
T3-RTE10	Manufacturing Technologies at Scale
T3-RTE11	Design for Systems level
T3-RTE12	For organics, efficiency needs to be improved, together with reducing the cost of material synthesis and purification. Operational stability is still a big issue.
T3-RTE13	OPV suffers from poor adhesion between PA and PEDOT:PSS - need a suitable replacement that is not deposited by evaporation
T3-RTE14	3D morphology for carrier lifetime/path length - especially for OPV - additives etc...
T3-RTE15	For organic PV: the exciting binding energy penalty
T3-RTE16	Making these materials in large enough quantities for large-scale deployment
T3-RTE17	Efficiency: further work to increase power conversion efficiencies through device structure and new materials design
T3-RTE18	Properties: Flexible, lightweight, transparent, conductive substrates with low series/charge-transfer resistance for flexible devices (Avoiding ITO).

APPENDIX VIII: SPECIFIC CHALLENGES AND ENABLERS FOR EMERGING INORGANIC MATERIALS

ID	Research challenges, enabling technology, other enablers
T4-RTE1	Direct generation of solar fuel (or NH3) using catalyst attached to QD
T4-RTE2	integrated QD-based LED emission/reabsorption, ink jet printing on curved glass, e.g. ink jet printing on curved glass
T4-RTE3	Inverse design of defect tolerant semiconductors
T4-RTE4	New tools to accelerate the optimisation of transport properties
T4-RTE5	Linking together (computational, robotics) materials discovery, machine learning and device development
T4-RTE6	Low CAPEX (including lower temperatures), scalable manufacturing/deposition methods
T4-RTE7	Standards for characterising materials for PV applications
T4-RTE8	Better encapsulants and adhesive materials
T4-RTE9	Flexible and non-standard substrates
T4-RTE10	Access to equipment for measuring the long-term stability of devices
T4-RTE11	Definition of protocols and reporting (standardisation) for reporting the long-term stability of devices
T4-RTE12	Chemical compound guanidinium thiocyanate (GITC) are seen to dramatically improve the structural and optoelectronic properties of the lead-tin mixed perovskite
T4-RTE13	CZTS but the processing routes to high efficiency require the use of hydrazine. [manufacturing, design]

APPENDIX IX: LIST OF FIGURES

APPENDIX X: LIST OF TABLES