Strategic Research and Innovation Agenda on Photovoltaics

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List of Abbreviations

» **AgriPV** Agrivoltaics
» **AI** Artificial Intelligence
» **APC** Advanced Process Control
» **BIM** Building Information Modelling
» **BIPV** Building Integrated Photovoltaics
» **BOS** Balance of System
» **CAD** Computed-Aided Design
» **CAP** Common Agriculture Policy
» **CAPEX** Capital Expenditures
» **CdTe PV** Cadmium Telluride Photovoltaics
» **CED** Cumulative Energy Demand
» **CIGS** Copper Indium Gallium Selenide Solar Cells
» **CPV** Concentrating Photovoltaics
» **CSER** Climate-specific Energy Rating
» **CSP** Concentrated Solar Power
» **EEE** Electrical and Electronic Equipment
» **EII** Environmental Impact Index
» **EL** Electroluminescence
» **EMS** Energy Management System
» **EOL-RR** End-of-Life Recycling Rate
» **EPBT** Associated Energy Payback Time
» **ERoEI** Energy Return on Energy Invested
» **ETIP PV** The European Technology and Innovation Platform for Photovoltaics
» **EVs** Electric Vehicles
» **FPV** Floating Solar
» **GDPR** General Data Protection Regulation
» **GHG** Greenhouse Gases
» **GPP** Green Public Procurement
» **IE** Industrial Ecology
» **IEA** International Energy Agency
» **IIPV** Infrastructure-Integrated Photovoltaic
» **IoT** Internet of Things
» **IP** Intellectual Property

- **IPCC** Intergovernmental Panel on Climate Change
- **IR** Infrared
- **IRENA** International Renewable Energy Agency
- **IRR** Rate of Return
- **ISO** International Organization for Standardization
- **JRC** Joint Research Centre
- **LCA** Lifecycle Assessment
- **LCI** Life Cycle Inventory
- **LCoE** Levelized Cost of Electricity
- **LeTID** Light- and Elevated Temperature-induced Degradation
- **LTYP** Long-Term Yield Predictions
- **MFA** Material Flow Analysis
- **MLPE** Module Level Power Electronics
- **MPPT** Maximum Power Point Tracking
- **NFA** Non-fullerene Acceptors
- **nZEB** Nearly Zero Energy Buildings
- **O&M** Operation and Maintenance
- **OEM** Original Equipment Manufacturer
- **OPV** Organic Photovoltaics
- **PCC** Point of Common Coupling
- **PCM** Phase Change Materials
- **PDT** Post-deposition Treatment
- **PE** Primary Energy
- **PEF** Product Environmental Footprint
- **PEFCR** Product Environmental Footprint Category Rules
- **PERC** Passivated Emitter and Rear Cell
- **PID** Potential Induced Degradation
- **PIPV** Product Integrated Photovoltaics
- **PVPS** Photovoltaics Power System Programme
- **PVQAT** Photovoltaics Quality Assurance Task Force
- **RFID** Radio-frequency Identification
- **RoI** Return on Investment
- **SCADA** Supervisory Control and Data Acquisition
- **SCOSC** Single Component Organic Solar Cell
- **SHJ** Silicon Heterojunction Solar Cells
- **SME** Small and Médium Sized Enterprises

- » **SPE** SolarPower Europe
- » **SRIA** Strategic Research and Innovation Agenda
- » **TCOs** Transparent Conducting Oxides
- » **TF PV** Thin Film Photovoltaics
- » **TRL** Technology Readiness Level
- » **UAVs** Unmanned Aerial Vehicles
- » **UVF** Ultraviolet Fluorescence
- » **VAPV** Vehicle-applied Photovoltaics
- » **VIPV** Vehicle-integrated Photovoltaics
- » **Voc** Volatile Organic Compounds
- » **VPPs** Virtual Power Plants
- » **WACC** Weighted Average Cost of Capital
- » **WEEE** Waste from Electrical and Electronic Equipment

This document was presented to the European Commission on meetings with DG RTD, DG JRC, and DG CLIMA on 9 November 2021 and a meeting with DG ENER in December 2021. It was also presented to technical specialists from DG JRC in five challenge-specific meetings between the 24th January to 31st January 2022. Meeting participants were able to ask questions and give feedback on the report; their feedback has been incorporated into the final version of this SRIA.

Solar PV will play a prominent role to achieve the EU's clean energy targets and global sustainability goals.

Introduction

The Strategic Research and Innovation Agenda (SRIA) developed by ETIP PV with significant input from EERA-PV covers photovoltaic science, technology, and applications in Europe. The European Green Deal, the Fit for 55 package, the Paris Agreement, Horizon Europe, and even the 2020 European Recovery Plan have placed climate neutrality by 2050 at the heart of Europe's socio-economic future. Electricity is the cornerstone of decarbonized modern energy systems globally, and solar and wind rang among key energy sources to deliver this electricity in sufficient quantities affordably and sustainably. Solar PV will thus play a prominent role to achieve the EU's clean energy targets, as well as global sustainability goals. Solar PV technology has already proven to be economically and environmentally competitive, though to become a major player of the clean energy system, it must successfully address further challenges related to device innovation, manufacturing, integration, and circularity. The SRIA presents overarching challenges on facilitating a transition to solar energy in Europe through PV technology and furthermore analyses five interlocking challenges of PV research & innovation.

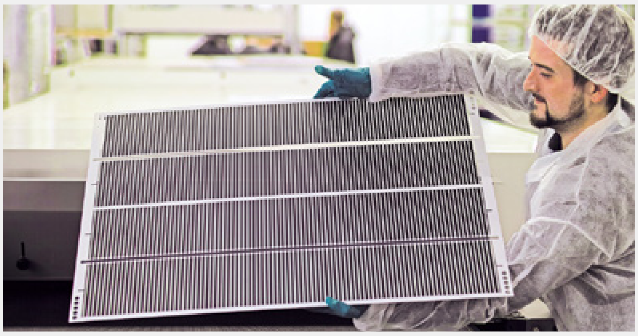
Challenge 1 is focused on measures to enhance the performance and reduce costs of advanced PV technologies and manufacturing processes. This focus is key for all subsequent sections; in order for PV to fulfil its goals of fundamentally transforming the European energy system, the sector must be characterised by affordability, efficiency, and sustainability. Therefore, the first challenge is to outline research & innovation needs for performance enhancement covering all components of a PV system including their production. To provide specific research needs and identify modules with higher efficiency and lower costs, Challenge 1 examines individual types of PV modules: silicon PV modules, perovskite PV modules, thin-film (non-perovskite) PV modules, and tandem PV modules. This section also outlines other measures to enhance performance and reduce costs, namely improving system design and introducing digital technologies. Building upon themes of improving system design, **Challenge 2** details lifetime, reliability, and sustainability enhancements through advanced PV technologies, manufacturing, and applications. This is broken down into an objective of sustainable and circular solar PV (through an R-ladder of circularity) and an objective of reliable and bankable solar PV through roadmaps ranging from quality assurance measures to eco-labelling and energy-labelling tools for life cycle assessment.

Each challenge section includes specific objectives, as well as certain roadmaps to achieve that objective.

For clarity and consistency across the report and to compare certain objectives' innovation potential, each roadmap includes four subsections: rationale for support; status; targets, type of activity and TRL; and KPIs for 2030.

Challenge 3 segues from design and manufacturing themes to ones of application. In particular, the section discusses new applications for PV integration to create diversified and dual-purpose deployment and therefore enhance value. Six physical integration applications are analysed: building integrated PV (BIPV), vehicle integrated PV (VIPV), agrivoltaics/landscape integrated PV, floating PV, infrastructure integrated PV, and low-power energy harvesting PV. By integrating PV technology into the built European environment, the PV sector can create huge opportunities for European value and job creation. The central theme of PV integration continues in **Challenge 4**: smart energy system integration of photovoltaics for large-scale deployment and high penetration. This challenge particularly embraces the potential of digital technology such as fostering more intelligence in distributed control, developing hybrid and integrated systems for greater flexibility and efficiency, and supporting aggregated energy and Virtual Power Plants.

Challenge 5 differs from the other sections by focusing on socio-economic aspects of the PV energy transition rather than specific PV technologies. It emphasises the need for higher awareness of solar PV-related externalities and benefits and also identifies the economic and sustainability benefits of incorporating PV technology. It concludes with a set of recommendations to increase support, fund research and innovation, and engage with stakeholders and policymakers. Each challenge section includes specific objectives, as well as certain roadmaps to achieve that objective. For clarity and consistency across the report and to compare certain objectives' innovation potential, each roadmap includes four subsections: rationale for support; status; targets, type of activity and TRL; and KPIs for 2030. This method therefore touches on the importance of a specific practice/technology (such as vehicle integrated PV), analyses its current status, provides an overview of research stages and actions, and identifies key indicators for future success.



↑ Screen-printed photoelectrode of a perovskite solar module. © Fraunhofer ISE

Solar PV energy has a very large potential globally as well as in Europe.

Its current contribution to global electricity demand is around 4 % and is rapidly growing.

SRIA Overarching Challenges Making the Energy Transition a European Success

Renewable electricity is a cornerstone of the energy system of the future

Whether at global or European scale, electricity is the cornerstone of decarbonized energy systems.[i] Solar energy and wind energy are the key technologies to deliver this electricity in sufficient (i.e. very large) quantities, at affordable cost, in an environmentally & societally sustainable way. A massive rollout, integration into the energy system and our living environment, and the circularity of the entire value chain is needed in order to successfully lead the energy transition.

Potential and forecast of the solar photovoltaic (PV) development have been studied in number of scenarios and visions. Should they vary in the pace and scale of PV deployment, they demonstrate an increasingly converging view on the necessary deep electrification of most economic sectors enabling a climate-safe future, and the prominent role of solar PV. Solar energy will eventually become a major supplier of our carbon-free electricity. This is illustrated in the visionary global '100 %-renewables scenario' of the LUT-group in Finland,[ii] its translation to Europe[iii] as well as the ETIP PV Vision,[iv] but also in IRENA's Roadmap to 2050 [v] or Shell's Sky Scenario.[vi]

Consistent with these prospects, the European Green Deal has set ambitious goals for energy transition in line with the Intergovernmental Panel on Climate Change (IPCC)[vii] recommendations. On 21 April, European Parliament and Council agreed to a legally binding cut of emissions by at least 55 % by 2030 compared to 1990 levels and climate-neutrality by 2050. [(1)] The latest declarations confirm that the EU energy system decarbonization is considered an enabler for the 2030 and 2050 climate objectives: "A power sector must be developed that is based largely on renewable sources" and "At the same time, the EU's energy supply needs to be secure and affordable for consumers and businesses." The EC has estimated that renewables must account for 38-40 % of final energy demand by 2030 to meet the 55 % target. [(2)]

Massive rollout and integration of solar energy at affordable cost, in an environmentally & societally sustainable way

Solar PV energy has a very large potential globally as well as in Europe. Its current contribution to global electricity demand is around 4 % and is rapidly growing. Its contribution to electricity demand in the EU is around 3 % on average, and it is already considerably higher in several EU member states: e.g. 6 to 7 % in Belgium and the Netherlands, and 8 to 9 % in Italy, Greece and Germany.

(1) https://www.consilium.europa.eu/en/press/press-releases/2021/05/05/european-climate-law-council-and-parliament-reach-provisional-agreement
(2) See preamble to RES Directive public consultation

Solar energy massive rollout, which paves the way towards the EU 2050 objectives, requires addressing a range of challenges at the same time:

» Further reduce the solar PV generation cost. Reductions here will offset increases in energy system cost due to batteries or other storage technologies.

» Make solar PV readily available for a range of various applications. PV not just as a standardised 'add on' module, which helped to make the technology affordable, but increasingly also as an integrated multipurpose solution. Think, for instance, of electricity-generating buildings, car roofs, and many other surfaces. Think also of PV systems integrated into infrastructure (roads, noise barriers, dikes, etc.), PV in combination with agriculture (agri-PV) and PV in combination with land or water management to enhance biodiversity or services (eco-PV).

» Develop circularity of the PV systems various components.

PV will challenge new markets: power to heat, fuels & products (often referred to as power-to-X; P2X) and other options for enhanced flexibility to match generation and demand, from the levels of individual users to the entire regional, national, or international energy systems.

Supporting Economic Recovery and Building the Value Chains for Renewables

Achieving the aim of the Green Deal to make Europe's economy sustainable goes hand in hand with the EU's economic recovery.

The PV industry has changed radically in recent years. In Europe, the rapid growth of the PV market has not led to similar growth in PV manufacturing capacity as policies have focused on supporting the generation and use of PV electricity. As a result, Europe has lost considerable industrial market share over the last 10 to 15 years. While 30 % of global PV manufacturing was done in Europe in 2007, it has fallen to less than 3 % today., with an annual turnover across the European PV industry currently estimated at €5 billion.

Although the global PV market has grown rapidly for decades already, most of the global deployment is yet to come. Only 1 or 2 % of the cumulative PV capacity anticipated in 2050 has been installed so far. This illustrates the huge opportunities for PV sector in manufacturing, installation and all other parts of the value chain. In a context where currently almost all PV cells and modules are produced outside Europe and particularly in China (over 70 %), and where there is still plenty of room for breakthoughs in technology, manufacturing and applications, industry must be developed hand-in-hand with research and innovation capacity to stay at the forefront of technology development. Beyond the related socio-economic benefits, this ambition is aligned with the Commission's "New Industrial Strategy for Europe" vision: a source of economic growth, quality jobs creation and, last but not least, strategically increased sovereignty. It also matches the Commission's Circular Economy Action Plan, in particular through the European Solar Initiative, launched on February 23rd 2021 by SolarPower Europe (SPE) and InnoEnergy. Building upon the strong momentum offered by the Solar Manufacturing Accelerator launched in 2020 by key stakeholders[viii] of the European PV value chain and the notable activism of some of them, it gathers today the support of Commissioners Thierry Breton and Kadri Simson.

European industry success in the global competition relies upon high market ambitions, rapid innovation and a future-ready sustainable value chain.

Recent rapid cost reductions in setting up PV manufacturing capacity, coupled with a large increase in demand for the various forms PV can take, should trigger "made in Europe PV". CAPEX costs for polysilicon, wafer, solar cell and module manufacturing plants have decreased by 75 to 90 % between 2010 and 2018. Economies of scale for silicon-based manufacturing are critical, and a recent study has shown that a European value chain would be competitive with huge PV factories, each with an annual production volume between 5 and 10 GW. Combined with the ambitions for large-scale deployment, this offers a promising perspective on PV manufacturing in Europe.

Looking beyond the technologies currently available on the market and their emerging advanced versions, Europe has a world-leading position in research and development of novel approaches, including ultra-fast roll-to-roll manufacturing of next-generation PV technologies such as perovskites which are much less dependent on scale. These technologies enable a range of new, integrated applications, which are vital for large-scale deployment in a societally and environmentally sustainable way.

Utilising Circularity to Ensure a Sustainable Transition

Large-scale use of PV requires the sector to become fully circular. Circularity will have to be achieved while maintaining the already proven strengths of PV in terms of cost, performance, and reliability. It will thus be given an increasingly important place in the research, innovation and manufacturing sectors. Providing the best solutions that take these requirements into account is an opportunity for the European PV sector to build up new manufacturing capacity. Strategies for circularity are encompassed with the "R-ladder" strategy (refuse, rethink, reduce, reuse, repair, remanufacture, repurpose, recycle, energy recovery).[3] As a circular economy covers the entire lifecycle of a product, it requires a broad and systemic approach to production.

Although the global PV market has grown rapidly for decades already, only 1-2 % of the cumulative PV capacity anticipated in 2050 has been installed so far.

Industry must be developed hand-in-hand with research and innovation capacity to stay at the forefront of technology development.

(3) Minguez, Rikardo & Lizundia, Erlantz & Iturrondobeitia, Maider & Akizu-Gardoki, Ortzi & Saez de Camara, Estibaliz. (2021). Fostering Education for Circular Economy through Life Cycle Thinking. 10.5772/intechopen.98606.

CHALLENGE 1

Performance Enhancement and Cost Reduction through Advanced PV Technologies and Manufacturing

In the last decades, the cost of electricity produced from photovoltaics (PV) has decreased strongly, enabling PV to be crowned as the king of electricity markets [F. Birol, IEA Annual Energy Outlook 2021] and to become one of the major pillars of the future energy system.

For PV to fulfil its mission in transforming the energy systems and to accommodate large-scale deployment, further cost reduction as well as increased emphasis on efficiency and sustainability is necessary.

The energy output of PV modules can be enhanced by increasing the efficiency or energy yield (MWh/Wp) or a combination of these factors. Since Balance-of-System (BOS) cost is becoming a larger fraction of the overall cost, increasing the energy output of modules will directly affect the levelized cost of electricity (LCoE). Other factors could also impact the BOS cost. For example, the application of lightweight modules could, dependent on the application, relax the requirements for the robustness of the system aspects, and therefore reduce the overall cost as well. Development of novel manufacturing technologies to increase the efficiency and to further reduce the production cost will result in lower LCoE. Besides cost and efficient use of the available areas, other factors such as spatial and ecological integration are important for large scale deployment of PV.

This Challenge is divided into three objectives:

- Objective 1: **PV modules with higher efficiencies and lower costs**
- Objective 2: **System design for lower LCOE of various applications**
- Objective 3: **Digitalisation of PV**

Together, these three objectives cover all aspects that need to be improved to lower the cost and enhance the efficiency of PV technology to ensure a large deployment and the various applications needed to make PV a cornerstone of the future energy system.

← In order to produce high-efficiency PERC solar cells in series, Dr Jan Nekarda and Dr Ralf Preu developed the Laser-Fired Contact (LFC) Process, which can be integrated simply and inexpensively into existing production processes by solar cell manufacturers. They were awarded the Joseph von Fraunhofer Prize in 2016 for this achievement. © Fraunhofer ISE

↑ Researchers are investigating the extent to which agri-PV systems can protect apples from harmful environmental influences. © Fraunhofer ISE

Objective 1: PV modules with higher efficiencies and lower costs

This objective focuses on improving efficiency and reducing costs of PV modules. It covers the various PV technologies that have already reached industrial maturity level as well as emerging technologies. These technologies are presented in four roadmaps based on the active material used and the number of junctions.

Higher efficiencies are of particular importance for several reasons:

i. Most PV system costs scale with the area, not only PV module costs but also those of many BOS-components. Thus, increasing the Wp/m² or ultimately kWh/m² through higher efficiencies is a very strong leverage for reducing LCOE.

ii. Increasing electrification of our energy system and the growing demand for electricity from sectors like heating and cooling, transport and chemical conversion require high performing electricity generation. In urban Europe, local electricity generation and storage can reduce transmission costs substantially but **available area** on buildings, vehicles, infrastructure etc needs to be used as effectively as possible.

iii. In a multi-TW PV industry also other **resource constraints** become challenging, ranging from metal depletion to available production capacities. Again, higher efficiencies can help to alleviate these constraints.

Roadmap 1: Silicon PV Modules

Rationale for support

Although China dominates the manufacturing of wafer-based silicon solar cells and modules, **Europe is a leader in the more advanced technology concepts, both single-junction as well as multi-junction approaches (see Roadmap 4: Tandem PV modules).** In particular, Europe's silicon PV sector (R&D and industry) has proven in the last decade that it can successfully bring novel technologies from the lab to the production environment, leading to higher module efficiencies and lower module costs. Continued R&D effort across the European value chain is imperative to maintain this leading position in silicon photovoltaics.

In summary, further R&D support in Europe in the field of silicon PV technology is needed and should focus on:

Achieving multi-GWp silicon cell and module manufacturing with low carbon footprint and circularity in Europe

Further lowering the LCoE of both utility-scale PV and Integrated PV

Maintaining and reinforcing Europe's leading position in silicon PV technology regarding high performance and lower costs, while at the same time achieving sustainability (see Challenge 2) and integration in the environment (see Challenge 3).

Status

As the global PV market has steadily increased, crystalline silicon technologies have remained the workhorse of the photovoltaic industry, accounting for 90 % of PV installed in the last 20 years.

The efficiency of commercial silicon PV modules has approximately been doubled since 2000 and prices have fallen by more than a factor of 20. These factors resulted in very low LCoE of 10 (Middle East)-50 (Germany)€/MWh.

Targets, Type of Activity and TRL

There remains huge potential for further innovation in performance, integration and sustainability enabling large-scale deployment, including the use of high-efficiency silicon PV as a bottom cell in hybrid tandem structures. That will allow efficiencies of over 30 % to be reached in the near future in hybrid tandem structures, and of over 40 % for multi-junction devices (see Roadmap 4).

Till 2030 different actions are needed to establish the targets from feedstock, over wafer and cells to modules:

Low-cost, high-quality silicon feedstock, ingots and wafers

» Early-Stage Research Actions (TRL2-3)

- Material and process development for direct band-gap silicon films enabling high conversion efficiencies

» Development Research Actions (TRL3-5)

- Efficient processes for low-cost crystal pulling of high-quality ingots with large diameters suitable for G12 (210 mm length) or larger wafers that allow for higher level of automation (industry 4.0 including digitalisation). Development of new knowledge and processes for low oxygen and other impurities, high minority carrier lifetime, and mitigating degradation effects such as Light and elevated Temperature Induced Degradation.

» Demonstration Actions (TRL5-7)

- Advanced processes for multi wire wafering of large (G12 and larger) thin (<130µm) wafers at low cost and with high final yield and final efficiency in the module. Development of automatic handling processes.
- Processes and technologies supporting cast-mono and high-performance multi-crystalline Si wafers such as gettering and improved casting methods.
- Process and equipment development for epitaxial wafers and alternatives (kerf-free);
- Reduction of cost, energy consumption, and other factors negatively impacting sustainability (e.g. water usage and CO_2 emissions from all stages including quartz reduction and production of high purity silicon feedstock). Of special interest here are epitaxial wafers and foils and other kerf-free technologies, and also the purification through the metallurgical route.
- Efficient and low-cost processes for recycling of Si from end of use and kerf from multiwire wafering.
- Efficient recycling process for silicon off-cut in ingot manufacturing (such as ingot tops, tails, side-cuts and off-spec material).

» Flagship Actions (TRL7-8)

- Further development and supporting processes for diamond-wire cutting of multi-crystalline wafers in order to save material (reduce kerf loss), process time and cost. E.g., nanoscale texturing for diamond-wire cut surfaces.
- Development of technologies for ingot pulling minimizing oxygen related stacking faults resulting in high overall yield over the ingot and high-quality n-type wafers and therefore a narrow efficiency distribution after cell processing.

Advanced silicon cell and module technologies

» Early-Stage Research Actions (TRL2-3)

- Process and material development for down and up conversion layers, or equivalents, as alternatives for tandems and enabling beyond 30 % conversion efficiency
- Nanophotonic structures to maximize absorption in ultrathin (<20 um) silicon solar cells enabling reduced silicon consumption and higher efficiencies (beyond 30 % possible because of high Voc due to higher carrier concentration)

» Development Research Actions (TRL3-5)

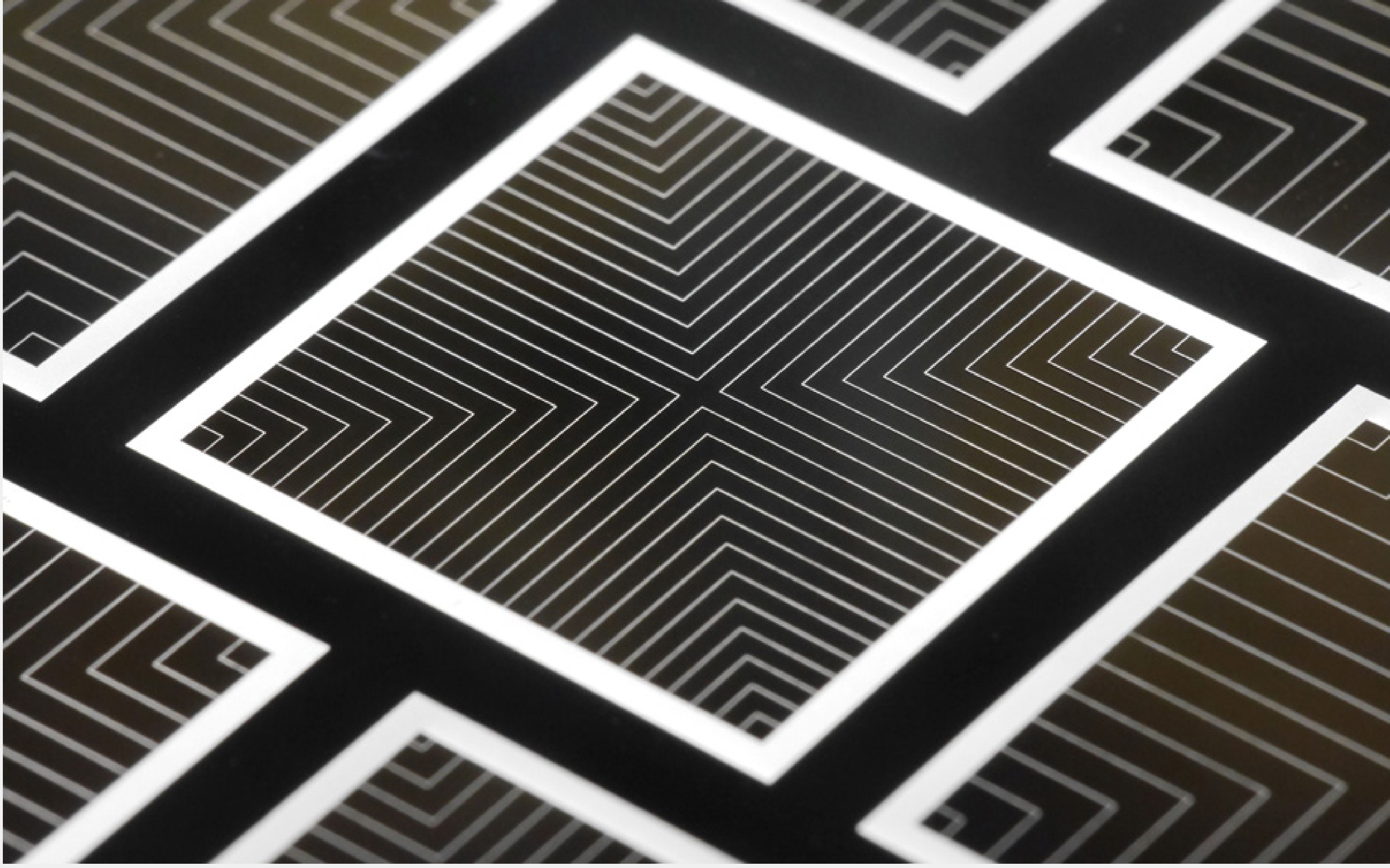
- Innovative texturization and light-trapping concepts for thin and ultrathin solar cells
- Advanced low-cost surface passivation and novel passivating contacts, novel heterojunctions, etc. (polySi alloyed with C or O; dopant free transparent passivating contacts, amorphous/nc-Si alloyed with C or O; material research, opto-electronic properties); including thin/ultrathin solar cells, and enabling >26 % cell efficiency for G12 wafers
- Knowledge development of degradation mechanisms in modules during heavy stress conditions in the field and mitigation procedures
- Development of low stress metallization and interconnection technologies for thin/ultrathin solar cells and improved reliability
- Technology development for circular design of c-Si based modules, considering sustainability and environmental aspects: energy /water consumption, avoidance of scarce and toxic materials, re-use of components, etc.
  - Reduction or replacement of critical raw materials such as silver, indium and fluor to enable sustainable growth of PV. Example: Low-cost and Ag-free metallization including, but not limited to, Cu plating, Fluor free module materials, TCOs using abundant materials (In free), such as AZO. Crucial here is that the novel materials and processes should not lead to efficiency nor reliability and longevity losses.
  - So-called up-cycling (which is actually recycling and maintaining high value; also for Ag and high-value Si)
- Development of aesthetical modules (freedom in colour) with maximum loss of 10 % relative compared to full black modules
- Development of 3D-shaped modules enabling integrated and customized products

» Demonstration Actions (TRL5-7)

- Development of technologies and equipment for highly automated (industry 4.0 including digitalisation, and for tens of GW production facilities) cell and module manufacturing enabling processing of M10 wafers or larger. The solar cells should be based on passivating contacts (polySi or silicon heterojunctions with doped amorphous silicon electron and hole contacts and have >25 % cell efficiency for different cell designs (front and back contacted and back-contacted)
- Development of improved module technology for higher performance: cut cells (incl. edge passivation), novel interconnection such as shingling or alternatives to maximize packing density / output power, bifacial, back-contacted, design and materials for longer operating lifetimes, avoiding/managing local heating in high-power modules
- Technology and processes for thin Si cells including excellent passivation, advanced light management, low-stress metallization and interconnection)
- Development of light weight modules enabling reduction of system cost
- Development of lead-free interconnection technology and metal pastes for cell contacts
- Development of fluorine-free back sheets for modules that lead to similar module lifetimes as conventional back sheets

» Flagship Actions (TRL7-8)

- Development of advanced processes and equipment for low cost and high throughput production of highly efficient and advanced homojunction c-Si cells (for example poly-Si, back-contacted) and modules (for example novel interconnection, high packing density) in GW scale with low material usage and low energy consumption
- Development of improved module technology for heterojunction cells: cutting of cells (including edge passivation), novel interconnection such as shingling or alternatives for high packing density, bifacial, back-contacted, design and materials for longer operating lifetimes, avoiding/managing local heating in high-power modules



The TOPCoRE solar cell achieved 26 percent efficiency, a new world record for both-sides-contacted solar cells.
© Fraunhofer ISE

KPIs

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value (2030)
Manufacturing Capacity	100 GW_p silicon-based cell and module manufacturing capacity with low carbon footprint in Europe
Performance and Sustainability	High-performance and sustainable PV with LCoE of 25 €/MWh at medium irradiation levels of 1300 kWh/(m²a), e.g. in southern Germany for utility-scale PV and <50 €/MWh for 'Integrated Photovoltaic' elements [(4)] European players as world leaders regarding high performance and sustainable silicon PV technology and its integration in the environment. • 25 % module conversion efficiency measured under standard test conditions and 40 year lifetime • Energy return of investments of more than 50 in southern Europe
Supply	Ensure the supply of critical raw materials like silver to a multi-terawatt industry.

(4) See also: Fraunhofer ISE, Levelized Cost of Electricity- Renewable Energy Technologies (2021)

Roadmap 2: Perovskite PV modules

Rationale for support

Europe is the leader of perovskite-PV as the most promising emerging PV technology as well as multi-junction approaches (see Roadmap 4).

Metal halide perovskite-based PV ('perovskite-PV' or 'Pk-PV' for short) has been the subject of research in the last decade having the advantage of

- use of abundant materials together
- low material and energy usage
- potential low-cost and high-speed production methods

As a thin film PV technology, Pk-PV can be produced on different "passive" substrates like glass (rigid or flexible), or foils, or another solar cell in the case of multijunction modules. Any form of Pk-PV cell is easy to layer on top of and connect to another cell. Pk-PV can be produced in opaque or transparent or anything in between, making it highly versatile PV technology.

Status

Industrial activity

Several companies are currently setting up pilot production lines in Europe [(5)], [(6)], Evolar is focusing on semi-transparent perovskite on glass as an upgrade for existing PV modules like cSi or CIGS with the 4-terminal approach, where current PV module top glass can be replaced by a glass containing the semi-transparent Pk-PV module. Saule Technologies is focusing on flexible Pk-PV made by ink jet printing, with sheet-to-sheet processes today, but with the intention to move to roll-to-roll production. Solaronix' pilot line produces currently opaque Pk-PV on glass. In China, meanwhile, GCL New Energy is producing semi-transparent and hence bifacial perovskite modules with non-certified efficiencies of 16 % on 40 x 60 cm² glass on a 10 MW line that will soon be joined by a 100 MW pilot line. The company has plans for a 1 GW production line in 2022.

Efficiencies

Pk-PV's power conversion efficiency in a single-junction architecture has increased from 3.8 % at its discovery in 2009 to an impressive 25.5 % in 2020. With that, Pk-PV has joined three other PV technologies (cSi, GaAs and GaInP) in reaching at least 75 % of their Shockley-Queisser performance limits. A module efficiency record of 17.9 % was achieved in 2020 by Panasonic on an aperture area of over 800 cm².

Scalable processes have been adopted for the various deposition methods for the perovskite absorber layer as well. [(7)] Successful demonstrators have been produced by applying single step wet deposition by coating or printing of the perovskite precursors, followed by a quenching step. Also, single-step precursors co-evaporation have yielded highly efficient perovskite absorber layers. Several groups are also investigating the dual step approach, where first a single layer of one of the precursors is applied by wet deposition or (co-)evaporation, followed by the deposition of the other precursors by wet deposition.

Stability

Early Pk-PV had poor stability but it has improved. [(8)] By selecting the right device architectures, materials and processes, several companies and research organisations can now make modules meeting one or more stress test standards (IEC 61215).

Lead

The best performing Pk-PV single-junction modules today contain a small amount (0.3-0.6 g/m²) of lead. Although the total amount of lead in the modules is low, the lead is quite mobile and there is therefore a risk of leakage into the environment. For this reason, research is ongoing into the use of lead-free perovskite materials as well as into ways of ensuring that the lead cannot escape from the modules.

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(5) Snaith, Nature Materials 2018, 17, 372–376. https://doi.org/10.1038/s41563-018-0071-z
(6) Ibid.
(7) Park & Zhu, Nature Reviews Materials 2020, 5, 333–350 (https://doi.org/10.1038/s41578-019-0176-2)
(8) Khenkin et al. Nature Energy 2020, 5, 35–49 (https://doi.org/10.1038/s41560-019-0529-5)

The long-term final vision for perovskite-only PV technologies is that they will be produced at very low costs, will ultimately be highly efficient and stable and in common with other non-Pk-PV technologies could be made into a very broad scope of different embodiments: flexible or rigid, opaque or semi-transparent or translucent.

Targets, Type of Activity and TRL

In case of single junction Pk-PV, it is expected that module efficiencies will be comparable to current existing PV technologies within 5 years. Depending on the learning curve, Pk-PV module manufacturing could quickly achieve comparable costs compared to currently commercial technologies. [9]

The long-term final vision for perovskite-only PV technologies is that they will be produced at very low costs, will ultimately be highly efficient and stable and in common with other non-Pk-PV technologies could be made into a very broad scope of different embodiments: flexible or rigid, opaque or semi-transparent or translucent. This gives perovskite PV the potential to address almost all of the requirements for a seemingly endless list of applications in the domains of IIPV, BIPV and VIPV but also for consumer electronics and IoT applications.

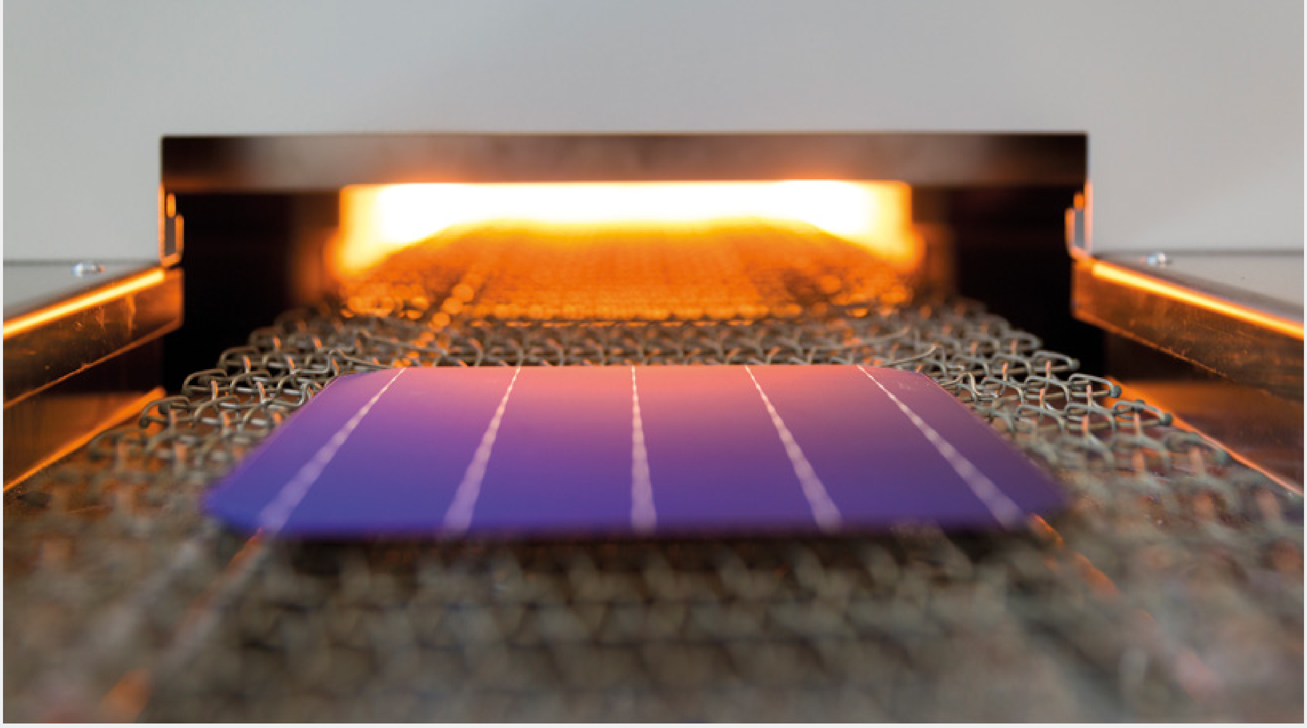
» **Early-Stage Research Actions (TRL 2-3)**

- Understand charge formation and charge movements on atomic level. This will help in further improve efficiency, intrinsic lifetime and material usage
- Lead-free Pk-PV
- Pk-PV with features to immobilize lead in case of catastrophic events
- Utilise Low-cost, high performing and fast processable transparent electrodes for perovskite PV through novel materials/processes
- Resolve stability issues of perovskite absorber/solar cells
- Develop recycling strategies for early stages of new (thin film) PV technology
- Integrate UV and IR absorbing perovskites for PV windows with transparency in the visible light range

» **Development Research Actions (TRL 3-5)**

- Evaluate impact of device design (n-i-p versus p-i-n stacks) and deposition techniques on manufacturability
- characterisation to enable industrial uptake through standardization
- Develop industrially feasible processes and equipment for reliable, low cost and high throughput production of perovskite solar cells with low material usage, low energy and material consumption
- Explore co-evaporation processes to ensure controlled and reproducible environment
- Develop soft deposition processes for TCO layers to reduce damage of sensitive substrates, e.g. organic materials or perovskites
- Improve surface passivation of perovskite layers
- Replace toxic solvents with solvents with less health and environmental impact

(9) L.A. Zafosching et al., IEEE Journal of Photovoltaics 10(6) (2020)



↑ Photovoltaic Technology Evaluation Center inaugurated in 2006 at Fraunhofer ISE was the first non Profit R&D laboratory in the field of crystalline silicon solar cells based on large scale and mostly automatic equipment. © Fraunhofer ISE Foto: Dirk Mahler.

» **Demonstration Actions (TRL 5-7)**

- Demonstrate at pilot level highly efficient and long-term stable semi-transparent and also bifacial perovskite PV single junction on glass for integrated Photovoltaics, later extension to hybrid 4-terminal applications on different cSi, CIGS and CdTe PV modules
- Demonstrate at pilot level highly efficient perovskite PV single junction on foil by using roll-to-roll processes
- Demonstrate industrial viability of perovskite technology including by transferring industrial thin-film processes from CIGS and CdTe to Pk for low-cost tandem cells

» **Flagship Actions (TRL 7-8)**

- European pilot line (~ 100 MW) for glass-based bifacial Pk-PV modules with the option to extend to higher efficiency all-perovskite PV multi-junctions to demonstrate low-cost material and processes for the production of modules with high throughput, low-energy consuming processes
- European pilot line for roll-to-roll bifacial Pk-PV production with the option to extend to higher efficiency all-perovskite PV multi-junctions to demonstrate low-cost material and processes for the production of modules that should allow to go to multi GW_p production capabilities with one single roll-to-roll production line

KPIs

Our vision is that in 2030, Pk-PV will have become the thin film technology with the highest market share for roof-top and utility-scale applications. For 2030 European Pk-PV R&D should achieve the following KPIs:

KPI	Target Value (2030)
LCoE	LCoE of Pk-PV technology should be equal to or lower than that for c-Si
CO_2 footprint	The yield-specific CO_2 footprint of Pk-PV technologies should be <80 % of c-Si production and Pk-PV modules should be fully recyclable.
Manufacturing and Commercialisation	Commercially available, Pk-based modules with an efficiency of >23 %

Roadmap 3: Thin-film (non-perovskite) PV modules

Rationale for support

Like Pk-PV, non-Pk thin-film PV cells and modules are challenged to achieve high efficiency and long lifetime at competitive production costs that should result in low LCoE. Amorphous silicon PV technology has failed primarily due to too low module efficiency (not reaching the threshold of 15 %). CIGS and CdTe PV technologies are mature inorganic thin-film PV technologies that exceeded the 15 % threshold with proven long-term stability but have not taken market share or grown as Si-PV has.

Thin-film PV devices bring the following advantages

» can be placed directly on substrates of all shapes and curvatures to add an electricity-generating capability to many kinds of objects;

» can be 0-100 % opaque;

» have the potential to open up new markets that are difficult to access for wafer-based modules;

» use few materials.

that can be decisive for specific integrated-PV applications.

Mature inorganic thin-films: CIGS / CdTe

These have high lab-scale efficiencies, good long-term stability [10] comparable to that of silicon-based modules under outdoor conditions and high potential for cost reduction. Due to superior low-light behaviour and a low temperature coefficient, the performance ratio of both CIGS and CdTe devices can be comparable to that of Si wafer-based modules with higher STC efficiencies. There is an opportunity for steep cost reduction in short space of time since economies of scale are not yet exploited like for Si.

Organic PV

The latest record OPV solar cell reached 18,2 % (on 0,03 cm²) and 15,2 % (on 1 cm²). There has been a great recent increase in efficiency as seen from adoption of non-fullerene acceptors (NFAs), low toxicity, and short energy payback times.

Kesterites

The most robust thin film PV alternative to amorphous-Si and CIGS is kesterites-based PV (CZTSSe) technology having the advantage of excellent availability and recyclability of earth-abundant raw materials not on the EU's 'critical' list. The latest record CZTS solar cell reached 12,6 % (on 0,42 cm²) and 11,3 % (on 1 cm²). Kesterites have demonstrated considerably long lifetime exceeding 30 years.

The limitations of the mature TF PV technologies encourage a continued search for new materials, as the established technologies face the challenges related to either the use of critical raw materials, toxic elements, long-term stability, conversion efficiency limitations, cost or low technological flexibility (e.g. incompatibility with flexible substrates or transparent concepts). The focus of continued exploratory research (low TRL) is on emerging absorbers that can bring additional benefits and/or may allow the development of novel applications.

Emerging oxides

In addition to the environmentally friendly material profile, transparency, p- and n-type conductivity, low-cost non-vacuum production methods are some of the advantages of Cu2O based PV.

Pnictides

Pnictides have gained increasing research interest due to their suitable band gap, excellent light absorption and electronic transport properties

Antimony-based chalcogenides $Sb_2(S,Se)_3$

This relatively earth-abundant and low-cost absorber has excellent light absorption capability (>105 cm-1 at short wavelength) and enables highly anisotropic charge-carrier transport due to its quasi-one-dimensional ribbon-like morphology, differentiating it from traditional cubic solar cell materials.

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(10) Prog. Photovolt: Res. Appl. 2017; 25:968–981, doi.org/10.1002/pip.2904

Status

Inorganic thin film PV technologies

CIGS and CdTe are mature and commercially available thin film technologies which show lab cell record efficiencies of 23.4 %[11] and 22.1 %[12], respectively, and mini module efficiencies approaching 20 %. Current commercial modules have aperture efficiencies in the range of 13-17 %, and existing production lines also show already today a relatively low carbon footprint per W_p on a module level.[13], [14]

The annual CdTe production is 7-8 GW_p[15] while the annual production of CIGS was approximately 1.6 GW_p in 2019[16] giving these technologies a market share of 6 % in 2019 (Fraunhofer ISE: Photovoltaics Report, updated: 23 June 2020).

However, economies of scale have not yet been fully exploited, in particular for CIGS.

Factors that currently limit the growth of CIGS and CdTe markets are the efficiency gap between record laboratory devices and production modules, the comparatively low production volume of CIGS compared to crystalline silicon devices and a higher investment risk.

Another concern that is often raised regarding CIGS and CdTe production is the fact that they use comparatively rare elements, regarded as critical raw materials by the European Union.[17]

Currently, a few companies, mainly in Asia, dominate the CIGS market: Solar Frontier, Japan is the largest CIGS producer, operating factories with 1 GW production capacity, while several Chinese manufacturers are building up production capacity. Europe has a long-standing track record of high (record) efficiencies and excellent know-how in manufacturing equipment, yet only a few European producers, mostly branches of Asian companies, are still active in CIGS production. In the case of CdTe, there is mainly one large producer, namely First Solar in the USA.

An excellent R&D landscape in Europe has built a track record of successfully transferring innovations and efficiency improvements into industrial production. European machine and equipment manufacturers are well placed to make Europe again the global leader for thin film technologies and initiate local production capacities, securing high value jobs through manufacturing and supply chain. Several R&D labs and pilot plants of international thin film PV module producers with a deep knowledge in industrialization and continuous product development are located in Europe.

Organic PV technology

The technology of Organic Photovoltaics (OPV) has recently achieved the record cell efficiency of 18,2 % (on 0,03 cm^2) paved by a staggering 50 % rise in efficiency in the last five years .[18] This is largely due to the introduction of a new class of electron acceptors, the so-called Non-Fullerene Acceptors (NFA). Considering the anticipated 100-fold rise in installed PV capacity by 2050,[19] scalable technologies relying on abundant elements with low toxicity and short energy payback will be required, positioning OPV as a green PV technology of the future.

For NFA based OPV, bulk heterojunctions have today reached efficiencies above 18 %,[20] using NFA molecules

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(11) M. Nakamura, K. Yamaguchi, Y. Kimoto, Y. Yasaki, T. Kato, H. Sugimoto, Cd-Free $Cu(In,Ga)(Se,S)_2$ thin-film solar cell with record efficiency of 23.35%, IEEE J. Photovoltaics. 9 (2019) 1863–1867

(12) National Renewable Energy Laboratory 2020 (available at: www.nrel.gov/pv/cell-efficiency.html)

(13) Solar Frontier, Avancis data sheets 2021

(14) Borowski et al 38th EU PVSEC 2021

(15) J. Phys. D: Appl. Phys. 53 (2020) 493001 (47pp)

(16) Photovoltaics Report, Fraunhofer ISE 2020

(17) https://ec.europa.eu/docsroom/documents/42849

(18) Green, M. et al. Solar cell efficiency tables (version 57). Progress in Photovoltaics **29,** 3 (2021)

(19) Bogdanov et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy, 227, 120467 (2021)

(20) Zhang, M. et al. Single-layered organic photovoltaics with double cascading charge transport pathways: 18% efficiencies. Nature Comm. **12**, 309 (2021).

from the new Y-family, e.g.Y6 (BTP-4F).[21] Besides enhanced infrared absorption explaining part of the efficiency rise for NFA OPV, a large fraction of the improvements comes from minimized voltage losses arising from charge generation at nearly zero energy level offsets, at electron donor and acceptor interfaces. The progress can also be linked to improved exciton lifetimes and diffusion lengths in these new NFA systems, compared to the fullerene-based electron acceptors, which opens a potential for simpler bilayer donor-acceptor architectures.

The record efficiency for OPV mini-modules currently stands at 13,6 % (on 66,6 cm²), and the typical efficiency of final products is 5–7 %.[22] With the first generation of OPV technology, lifetimes of up to 10 years were achieved under outdoor conditions and the cost of products have gone down by roughly a factor of 10 from 10 €/W_P .[23], [24]With upscaling to a GW level technology, costs as low as 5 €ct/W_P are predicted for OPV.[25]

Emerging thin-film technologies

New inorganic materials include chalcogenides ($Cu_2ZnSn(S,Se)_4$, $Sb_2(S,Se)_3$, $CuSbSe_2$, Cu_2SnS_3, Bi_2S_3, PbS etc.), oxides (Cu_2O) and pnictides (InP, Zn_3P_2, $ZnSnP_2$, $ZnSnN_2$, (In,Ga)N etc.). These technologies do not exist beyond lab scale but have shown enough development (stability, efficiency >5 % etc.) to identify them as potential future technological solutions:

Record efficiencies:

- $Cu_2ZnSn(S,Se)_4$ (CZTSSe) **12.6 %** [26]
- $Sb_2(S,Se)_3$ **10.5 %**
- CuO_2 **8.1 %**
- Zn_3P_2 **6.0 %**

Targets, Type of Activity and TRL

Like Si-PV or Pk-PV single-junction cells and modules, it is required that for all thin-film PV technologies their module efficiencies will be comparable to current existing PV technologies (module efficiency threshold of 15 %) within 5 years. At the same time, thin-film PV module manufacturing should quickly achieve comparable costs compared to currently commercial technologies.[27]

Mature thin-film technologies

For CdTe and CIGS, the main challenge will be to increase the production volume to profit from the scaling effects. Furthermore, the gap between laboratory devices and commercial modules has to be closed to reach competitive efficiencies and thus LCOE comparable to or better than for c-Si. Another challenge is to ensure the supply of critical raw materials like indium, gallium or tellurium to a multi-terawatt industry.

OPV

The main challenges are increasing efficiency for large areas (threshold of 15 %) and further increasing long-term stability. Since OPV will initially mainly serve (indoor) niche markets, the stability criterion is less severe than for standard outdoor modules.

Kesterites

Kesterite technology is sufficiently mature compared to other emerging TF PV (TRL 5-6) and continues to evolve from its current mini-module configuration towards further industry upscaling. The aim is to demonstrate within 5 years that this TF PV technology can reach the threshold of 15 % (both cell and module) to be considered for the market under solid competitiveness arguments (reduced manufacturing cost, short energy payback time of less

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(21) Li, S. et al. New Phase for Organic Solar Cell Research: Emergence of Y-Series Electron Acceptors and Their Perspectives. ACS Energy Lett., **5**, 1554 (2020)

(22) Brabec, C. personal communication

(23) Gambhir et al. The future costs of OPV – A bottom-up model of material and manufacturing costs with uncertainty analysis. Solar Energy Materials and Solar Cells, **156**, 49 (2016)

(24) Brabec, C. et al. Material Strategies to Accelerate OPV Technology Toward a GW Technology. Adv. Ener. Mat., **10,** 2001864 (2020)

(25) Machui, F. et al., Cost analysis of roll-to-roll fabricated ITO free single and tandem organic solar modules based on data from manufacture. Energy Environ. Sci., vol. **7**, 2792 (2014)

(26) Wang, W., Winkler, M. T., Gunawan, O., Gokmen, T., Todorov, T. K., Zhu,Y. & Mitzi, D. B. Adv. Energy Mater. 2014, 4, 1301465.

(27) L.A. Zafosching et al., IEEE Journal of Photovoltaics 10(6) (2020)

than 1 year, sustainability, long lifetime, high yield, excellent properties for BIPV, PIPV applications) with mature TF PV technologies.

Other emerging materials

Here, more fundamental problems have to be solved, above all the low efficiency of devices based on most of these materials. Here, more basic research is needed to overcome some of the observed barriers.

» Early-Stage Research Actions (TRL2-3)

Inorganic thin film technologies

CIGS

- Implementation of completely dry processing including surface cleaning after post-deposition treatment (PDT)
- Implementation of selective contacts in CIGS solar cell structures instead of band grading
- Improving the thermal stability of CIGS low band gap devices for applications in monolithic tandem devices

Organic PV technology

- Modelling and prediction of new organic materials combinations for polymer and small molecule organic solar cells
- Establish the coupling between morphology and functionality for both fullerene and non-fullerene acceptor materials and determine the principles for realising these with scalable processing methods
- Explore the possibilities of leveraging strong light-matter coupling with highly ordered non-fullerene acceptors, to realise simpler bi-layer structures for more stable, efficient organic solar cells
- “Simple” materials, like non-fused ring systems, or, to some extent single composites materials (SCOSC) for improved stability
- Organic semiconductors and semiconductor inks that are fully compatible with environmental and green processing
- Develop generic concepts for doping of organic semiconductors

Emerging thin-film technologies

- Novel thin-film absorber materials for reduced energy and material costs, including everything offering more yield
- High-throughput materials research in combination with simulation and Artificial Intelligence to identify new promising materials suitable as absorber or as other functional layer
- Search for high band gap absorbers

» Development Research Actions (TRL 3-5*)*

Inorganic thin film technologies

CIGS

- Increased consideration of sustainability: environmental impact, resource availability, recyclability, energy balance
- Exploit thin-film advantages such as the possibility of flexible and lightweight modules, semi-transparent modules, and control of size and shape of modules to open up new markets in the field of integrated PV
- Reducing the amount of active material in CIGS technology

Organic PV technology

- Interface and charge extraction layers for OPV, forming long time stable contacts
- Other alternative architectures including bilayer, graded bilayer, ultrathin layer OPV
- Lamination and packaging processes that can operate below 140 ° C compatible with roll-to-roll OPV processing
- High-quality barrier layers and *in situ* packaging, thin-film solution processed packaging for improved stability and longevity

Emerging thin-film technologies

- Develop and apply standardized/commonly approved material assessment approaches to carrier lifetime, characterisation of surface recombination, bandgap and possible degradation/change of these parameters
- Accelerated incorporation of concepts for performance improvements developed for traditional thin-film technologies (e.g. interface treatments, grain boundary passivation, etc.) to emerging TF PV technologies

» **Demonstration Actions (TRL 5-7)**

CIGS

- Realisation of in-line characterisation for process control utilizing digitalisation, machine learning tools and IoT concepts
- Mass customized BIPV laminates with various colours, transparencies and sizes fully compatible with classic facade elements

Organic PV technology

- High resolution patterning processes for OPV with feature sizes of 100 micron or lower
- Production processes for “Mass Customization” according to specific requirements for format and shape for integrated PV like BIPV or vehicle-integrated PV

» **Flagship Actions (TRL7-8)**

- Develop next generation production equipment for larger size modules, high yield and throughput and low energy and material consumption to leverage economies of scale and improve the environmental footprint for CIGS and CdTe thin film module production
- Production processes and equipment for “Mass Customization” according to specific requirements for format and shape for integrated PV like BIPV or vehicle-integrated PV (high TRL)

KPIs

In 2030, there should be a strong position of mature thin film, non-perovskite PV in the market due to the specific advantages thin film technology possesses. For 2030 European non-Pk thin-film PV R&D should achieve the following KPIs:

KPI	Target Value (2030)
LCoE	LCOE of CIGS and CdTe technology should be equal to or lower than for c-Si
CO_2 footprint	Indium or tellurium reduction by a factor of 3 per watt with efficiency > 20 % compared to 2020 standards
Materials and Manufacturing	Commercially available, Pk-based modules with an efficiency of >23 %
Market and Production	• 10 % global market share for CIGS and CdTe-based modules • Commercially available, flexible CIGS-based modules with an efficiency of >18 % • Commercially available, OPV-based modules with an efficiency of >15 % • Mini-modules available from emerging thin film materials with >15 %

Our vision for 2030 is that tandem technologies will reach a market share of more than 5 % and will be successfully transitioning from niche to mass market applications by 2030.

Roadmap 4: Tandem PV modules

Rationale for support

Modules made from tandem PV cells achieve higher efficiency than single-junction cells. As explained in the introduction of this objective efficiency is one of the main drivers to reduce cost, area requirement and resource demands.

Novel material systems, like perovskites, have made cost-efficient multijunction PV modules possible. They are an area where Europe has a high level of expertise. Supporting EU manufacturers will help them create skilled jobs and export earnings from a technology vital for the world for ecological and competitiveness-related reasons. Since questions remain about the reliability and scalability of perovskite technology, silicon-based tandems with III-V top material (the dominant technology) should also be further developed and explored. A threshold of 20 % efficiency for the tandem PV modules is anticipated.

Status

Multijunction III-V solar cells (based on III–V compound semiconductors) currently exhibit the highest conversion efficiencies and are applied in concentrating photovoltaics (CPV) and in space. While space is a stable field for commercial activities, only little commercial or industrial activity is visible for terrestrial CPV. The reason are the very high costs associated with the epitaxial deposition of the III-V materials. Since 2009 the record efficiency for a three-junction cell is 41.5 % from a GaInP/GaInAs/Ge upright-grown solar cell under concentrated sunlight [(28)] Adding p-n junctions increases efficiency, e.g. to 47.1 % at 143 suns in an inverted metamorphic six-junction cell structure based on III-V semiconductor material. [(29)]

On the other hand, silicon based tandem solar cells, especially perovskite-silicon tandem devices promise considerably lower costs and with 29.5 % efficiency. [(30)] They are being tested in the field. In the laboratory scale, Perovskite/CIGS, Perovskite/Perovskite, and Organic/Organic tandem devices are being investigated.

Researchers have not yet settled on the right number of terminals to put on tandem cells. Two terminal devices (2T) require series interconnection of the tandem sub-cells, but the resulting solar cell has similar features as current single-junction devices regarding module interconnection and system aspects. In four terminal devices (4T), the solar cells are operated independently, making the need for current matching obsolete but requiring adapted module concepts. Three terminal structures (3T) seek to combine the advantages of 2T and 4T concepts.

Targets, Type of Activity and TRL

Our vision for 2030 is that tandem technologies will reach a market share of more than 5 % and will be successfully transitioning from niche to mass market applications by 2030. The technologies will successfully demonstrate long-term performance comparable to the single-junction technologies, clear advantages in terms of LCOE and in the environmental footprint to be achieved. In consequence, technology acceptance will be high, and no risk premium must be paid to finance projects that use them.

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(28) R.R. King et al. Band-gap engineered architectures for high-efficiency multijunction concentrator solar cells, 24th EUPVSEC, Hamburg, Germany (2009)

(29) M. Green et al., Solar Cell Efficiency Tables (Version 57), Progress in Photovoltaics 29 (2020)

(30) from such modules by Oxford PV [Press Release (2020)]

A) R&D priorities independent of tandem cell materials:

» Early-Stage Research Actions (TRL2-3)

- **Absorber material** chemical compositions need to be finetuned for highest stability and maximum efficiency. This includes bandgap tuning and the development of absorber material combinations for application in triple-junction devices. The question of bandgap tuning is not trivial, as bandgaps change due to temperature effects and in 2T devices, current matching has to be achieved at elevated operational temperatures.

- For the best **optical performance**, **parasitic absorption** in adjacent layers, TCOs etc needs to be minimized and light management ensuring photons are absorbed in the best suited junction within the multilayer stacks needs to be developed. To this end **electro-optical modelling** frameworks have to be developed for 2T, 3T and 4T multijunction solar cells.

- Furthermore, perspectives for the replacement of certain elements that are critical either due to toxicity issues (e.g. Pb) or due to limited availability not compatible with multi-TW scale deployment (e.g. In) need to be developed. Concepts need to be developed and the critical issues need to be understood for maximizing circularity, **sustainability**, and recyclability.

» Development Research Actions (TRL 3-5)

- A task for many 2T tandem technologies is the development of stable high-quality **recombination layers** that interconnect the different sub-cells and ideally combine functionalities i.e. that of charge selective contacts, to reduce the number of overall layers.

- Concepts and **module technology** need to be developed for 3T and 4T architectures with regard to voltage- or current-matching, and the consideration of system aspects, e.g. module integrated inverters/ mpp tracking etc. For all technologies module technology needs to be further developed to enable customization, achieve light weight/flexibility (including packaging) and enable bifocality.

- **Characterisation** methods and equipment (inline, offline) need to be developed to enable loss analysis from material and sub cell/cell level up to module level, for guidance for target-oriented optimisation to realise the full efficiency potential. Furthermore, failure mode analysis and mitigation strategies are needed to maximize stability.

- Reliable **energy yield modelling** needs to be developed which considers all relevant effects, such as changes of the spectral conditions and temperature effects. Accordingly, **input data** should be generated to enable energy yield modelling for distinct climatic conditions.

» Demonstration Actions (TRL 5-7)

- **High-throughput** processing up to module level, i.e. including high-throughput interconnection and lamination technology needs to be demonstrated with advanced process (inline) monitoring.

- **Outdoor tests** and reliability testing must be undertaken. Solar cell and module development should aim at achieving the same stability as established single-junction technologies while transferring the tandem efficiency advantage into a **substantially increased energy yield**. To this end **power management** systems and electronics integration that maximize energy yield in rapidly varying illumination conditions (weather variation but also mobile applications) need to be applied.

- **Market opportunities** need to be evaluated in techno-economic analyses for more-than-two junction solar cells (multijunction solar cells), new applications (electric vehicles, drones, HAPS, space). Accordingly, business models for re-use and recycling strategies must be calculated.

» Flagship Actions (TRL7-8)

- The successful **integration of tandem technologies** needs to be validated across all potential applications (vehicle, building, infrastructure, power plant ...).

- **Pilot-lines** for solar cell processing and module production must be put into operation with high versatility to combine different PV technologies in tandem modules with different configurations.

B) R&D specific to tandem cell material

» Silicon bottom solar cells for silicon-based tandems

» Development Research Actions (TRL 3-5)

- **Low-cost Silicon bottom cells** with good red response and high voltage should be developed. Works include bottom cell adaptation for IR spectrum, different tandem compatible texture technologies, and bifocality.

» Flagship Actions (TRL7-8)

- **Pilot-line production of low-cost Silicon bottom cells** derived from hetero-junction technologies on the one hand, and alternatively derived from PERC and TOPCon technologies.

Perovskite/silicon tandem solar cells

» Development Research Actions (TRL 3-5)

- Long-term stable **perovskite absorbers** with the optimal bandgap for maximum energy yield under operation conditions. To realise these, formation of the absorber during the different possible **deposition processes** (wet-chemically, co-evaporation, hybrid-processing) needs to be understood more deeply.

- Deepen the understanding of the interface processes to optimise **recombination layers and the charge selective layers**, which might also enable reducing the number of layers through combined functionalities, e.g. by tunnel junctions.

- Develops **bifacial multi-junction perovskite PV devices** with suitable materials, e.g. for future vertical PV elements in noise barriers or on agriculture land areas.

» Demonstration Actions (TRL 5-7)

- **Demonstrate industrially feasible processes and equipment** for reliable, low cost and high throughput production of silicon-perovskite tandem solar cells with high efficiency, low material usage, low energy and media consumption.

» Flagship Actions (TRL7-8)

- **Pilot lines** showing the potential of different production pathways for perovskite silicon tandem solar cells and modules should be established in Europe.

Perovskite/Perovskite tandem technology

» Development Research Actions (TRL 3-5)

- Improve stability of perovskite **absorber layers with low band gap** (typically containing Sn) to be used as bottom cell

- **Develop stable high-bandgap absorbers** for the top-cell. Work on the absorber and charge-selective contact layers to reduce V_{oc} deficit for top cell absorbers with E_g > 1.65 eV.

- **Anti-reflection measures** and photon management to mitigate weak surface texturing

» Demonstration Actions (TRL 5-7)

- The **NIR (near-infrared) transparency** of the top cell needs to be improved, in particular by reducing the parasitic absorption in TCO layers.

- The **technology for monolithic 2T tandem modules** needs to be developed. This requires non-damaging (laser) scribing technologies and novel concepts for series interconnections.

Other Thin Film Tandem Technologies

» Early-Stage Research Actions (TRL2-3)

- OPV kesterites, oxides and pnictides used in a tandem need their **bandgap tuned** to complement the other cell's absorption (towards lower bandgaps in the case of OPV absorbing in the near infrared).

- Transparent electrodes and contact materials (e.g. from high-throughput material screening)

- **Electro-optical modelling** frameworks for the above-mentioned tandem technologies and associated materials.

PVD deposition tool with wafers after TCO deposition. © Fraunhofer ISE

» Development Research Actions (TRL 3-5)

- To enable CIGS as bottom cell in combination with a Pk top cell it is important to adjust the CIGS **material composition** to reduce the bandgap in the bottom cell while maintaining high efficiency. The CIGS bottom cell needs improved infrared absorption with improved performance under top cell filtered light, while preferably reducing the surface roughness to enable good homogeneous coverage for the top cell. Optimise post-deposition treatments for lower bandgap compositions of CIGS bottom cell to achieve smooth surface.

- Similarly**, contact and (transparent) electrode** materials, identified in low-TRL work from high-throughput screening) and processes need to be adapted to create effective recombination junctions at the front side of the CIGS bottom cell. This includes a.o. improvement of the thermal stability of the CIGS bottom cell to tolerate thermal stress from top cell deposition and for deposition of highly transparent TCOs and top-device deposition in monolithic configuration.

- The variety of materials in the full tandem stack requires specific development of technology for such monolithic 2T tandem modules. **Laser scribing technology** for cell-to-cell interconnection which is versatile but also selectively non-damaging for the complicated layer stacks requires dedicated tool and process development. **Novel concepts for series connections** can come into play to address these challenges in an innovative way.

» Demonstration Actions (TRL 5-7)

- A clear differentiator for thin-film tandems is its **potential to yield fully flexible devices and modules**. To gain market interest for this unique selling point, it will be crucial to demonstrate **scalable processes** for the full tandem stack and its interconnection for modules. While it's obviously best to show this for high performing and stable tandem materials and stacks as to be developed in above actions, the crucial points here should focus more on the **process flow development**. Large area homogeneity, conformality, accuracy etc are **quality parameters** that come into play. Processes with higher CAPEX should yield high-throughput thin film deposition with high quality to balance the overall **cost/performance ratio for final modules** at competitive level. Process conditions (like thermal budget) are additionally constrained when **flexible carriers** are introduced.

III-V/silicon tandem solar cells

» Development Research Actions (TRL 3-5)

- To reduce the amount of epitaxy required maximizing absorption through increasing optical thickness **photonic structures** or plasmonic elements need to be developed.
- The concept of **terrestrial CPV** should be re-evaluated considering new module concepts (especially hybrid modules which also capture the diffuse part of sunlight, micro CPV combined with self-assembly technologies) and improved tracking.

» Demonstration Actions (TRL 5-7)

- The overwhelming priority is to **reduce costs**, as efficiency are already the highest of any PV technology for III-V multijunction devices. The most important leverages that need to be demonstrated and for which equipment at an industrial scale needs to be developed are

  – **Low-cost high-throughput epitaxy** on large areas of III-V materials either via heteroepitaxy and subsequent lift-off or directly on Si substrates.

  – Low-cost high-throughput large area **epitaxial lift-off** (porous subsurface layers, spalling). In this context the reuse of the wafer/substrates needs to be maximised.

  – High-throughput **transfer** and long-lasting connection with silicon bottom solar cells or other substrates for epitaxial films

  – Low-cost processing of and especially the **replacement of lithographic steps.**

KPIs

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value (2030)
Efficiency	Efficiency of at least 5 % absolute above respective single junction technology
Lifetime	Lifetime of the tandem device is the same as the lifetime of the bottom single junction device.
Production	Production of additional junction for less than 8 €/m2

Objective 2: System design for lower LCoE of various applications

Whereas objective 1 focused on photovoltaic modules and the different technologies that need to be further developed to produce more efficient modules and lower cost, objective 2 focuses on the R&D needed for all other elements of PV systems besides the modules. Moreover, this objective also focuses on various ways how the energy yield of systems (independent of the technology used) can be improved.

Roadmap 5: Balance of System (BOS) and energy yield improvement

Rationale for support

The focus of cost reduction and efficiency improvements for the past few decades has been on upstream PV value chain segments, as PV modules have traditionally been the costliest component of a PV system. With the strong reduction of PV module prices, other parts of the value chain become more and more important for lower LCOE. Efforts should therefore be extended to other components apart from PV modules and other activities more focused on installation, operation, maintenance, decommissioning, etc. (the so-called “soft costs”). It is paramount that the PV sector pays more attention to the electrical energy yield of PV systems in real operating conditions (different climates, albedo, applications, mounting conditions, etc.). There are several factors that increase the overall electrical energy yield of PV systems, such as efficiency (objective 1) and the yearly electricity production (yearly kWh per kW_P).

Since very high efficiencies are already achieved in power electronic devices, apart from reducing costs, main efforts must be focused on improving reliability, durability, longer lifetime and on offering new functionalities related to the integration of PV. At the balance of system level, the highest priority must be given to the development of inverters, supporting structures (including trackers), electrical storage devices, energy management systems (EMS) and new component / solutions designs for specific applications (floating, AgriPV).

Status

Inverters- power electronics

A recent review of the technology and market situation for the PV Ecodesign Preparatory Study [31] identified 3 main inverter categories.

- Central inverters, up to 5 MW, mainly used in utility-scale power plants. The main advantages are simplicity in design and connection, and low O&M costs. Disadvantages include an in-

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(31) Preparatory study for solar photovoltaic modules, inverters and systems. (Draft)Task 1 report: Product scope, Dodd, Nicholas; Espinosa, Nieves; Bennett, Michael, JRC. June 2018

crease of mismatch losses under non-uniform operating conditions or higher installation costs.

- String inverters used for a wide range of plant sizes from a few kWs to large multi-MW installations. Their sizes can reach 200-300 kW. In principle, they are a better solution in plants with risk of mismatching losses, provide more granularity in monitoring, improve the operation and maintenance through data analytics techniques and simplify the replacement and repair.

- Module level power electronics (MLPE), mainly power optimisers (DC-DC converters) and micro-inverters (DC-AC). The long-term durability of such devices is a critical factor as replacing defective components at module level could be expensive.

In terms of power conversion efficiency, central and string inverter products from leading manufacturers typically have an efficiency of 98 % and above, with module level devices slightly lower (95 %). Regarding circuit topology, single and three-phase inverters with and without transformers are current options and are used depending on the technical network. [32]

Supporting structures

Supporting structures have become an important part in PV systems cost breakdown, especially in large PV plants, in which tracking systems are used more and more often. In high radiation locations, 1-axis tracking structures offers lower LCOEs than fixed supporting structures, despite costing more. The latest product updates address the need to adapt structures to new applications (e.g. agrivoltaics). Larger and heavier modules lead to larger occupation of area and larger wind loads, increasing the weight and usage of material. The lack of size standardization at module level makes tracker manufacturers adapt their products by creating a family of products suitable for different sizes and configurations (portrait, landscape, number of modules, different string configurations).

Energy Yield improvement

Concerning monitoring of PV energy production, current approaches use thermal sensors that are attached to the outside of PV modules and pyranometers or reference cells to evaluate irradiance at a given location. By replacing these with sensors laminated as part of the PV modules and/or integrated directly on the solar cells themselves, more reliable and properly distributed data would be achieved. This would help manufacturers monitor their systems' performance. A large amount of data generated by sensors correctly distributed on the PV field would allow the plant to be better modelled.

Targets, Type of Activity and TRL

By 2030, Balance of System components (electronic and structural) will be adapted to new PV module technologies and applications like bifacial technology. In countries with high PV penetration levels, solar PV will be inextricably linked to electricity storage, enabling investors and plant operators to maximise solar incomes and ensuring that solar energy is delivered when it needed or required.

PV modules will be selected and tuned for specific climates and applications. Novel characterisation and modelling tools will improve performance diagnostics and forecasting at cell, module, system and power plant level. PV systems will be equipped with intelligence in the form of electronics and sensors so that they can detect whether they are shaded or adapt their working current–voltage characteristics to temperature (see roadmap 7). The generated data from these sensors and electronics will build better models for array performance and for location- and application-adapted module design.

Finally, these intelligent and energy-yield optimised PV cells and modules will enable a faster integration of the various emerging PV applications in the urban environment and in the energy system of the near future.

Inverters

» Development Research Actions (TRL 3-5)

  - Develop integrated communication connection between inverters and other components (e.g. battery, PV modules, etc.) to automatically gather information (serial number, geolocalisation, etc.) of components and support the automatic creation of Digital Twins and PV Information Model.

(32) *PV Inverters - Basic Facts for Planning PV Systems. The inverter is the heart of every PV plant. SMA, 2017*

Automated cell interconnection on industrial cell stringer for 3-5 busbars. © Fraunhofer ISE

- Develop inverters with increased power density and reliability by introducing new wide bandgap semiconductors (GaN, SiC)

» Demonstration Actions (TRL 5-7)

- EPC and O&M -friendly design of inverters reducing typical failures found in the field (e.g. overheating). Introduce new features to enable semi-automatic field inspection techniques (e.g. Electroluminescence / Photoluminescence) through direct communication between inverters and drones or hand-held devices.

» Demonstration Actions (TRL 6-8)

- Develop inverters with the added features of grid forming and grid responsive requirements in support of frequency control. Inverters' behavior remotely controllable to depending on the grid-supporting services required from the plant.

Structures

» Development Research Actions (TRL 4-6)

- Mounting structures adapted to large PV modules by reducing the amount and nature of materials (especially those affected by international market prices
- Control strategies for trackers to optimise production for complex terrain PV plants sites, considering bifacial technologies.
- Optimised, lower-cost tracking systems. Tracking could be considered at an early stage in the design of specific modules suitable for the tracking setup.

» Development and Demonstration Actions (TRL 5-7)

- AI techniques to improve energy yield of tracking systems: optimisation and machine-learning algorithms, digital twins of trackers for design improvement and O&M activities.

Energy Yield improvement

» Development Research Actions (TRL 3-5):

- To enable large-scale manufacturing of PV modules with embedded sensors, research is needed on the seamless integration of sensors in PV modules:
  i. integration within the module laminate of thin-film transistors (TFTs) to be used as thermal sensors and thin-film photodetectors (TFPs) to be used as optical sensors;
  ii. integration within the module laminate of glass fibres (or other waveguides) with distributed Bragg reflectors to be used as temperature and strain sensors;
  iii. integration of sensors directly on the solar cell, e.g. stress and temperature sensors
- Use STC analysis for energy evaluation under realistic conditions for module design and cost analysis.

- Develop passive (such as adding a heatsink to the rear side of the PV module, the use of phase change materials (PCM), and optical filters) or active cooling elements to keep the operating temperature low and uniform over the module area.

- Develop reconfigurable PV modules that are shade-tolerant and can deal with dynamic changing illumination conditions.

» Demonstration Actions (TRL 5-7):

- Standardisation: the IEC 61853 Energy Rating series needs to be updated to include a procedure for bifacial and multijunction climate specific energy rating (CSER). Over time, this type of standard should complement STC from the early stages of laboratory development to analysis of the PV field in operation.

- Combination of degradation analysis and energy yield analysis. Module warranty to be linked to energy produced under realistic conditions rather than an efficiency metric to increase energy production.

- Including climate and environmental assessments/ site assessment/novel technology in PV system design (what to build / where and how) through advanced GIS technologies

Other areas

» Demonstration action (TRL 6-8)

- Demonstrate that ICT technologies can contribute to the security and safe operation of PV plants (blockchain for energy-money transactions in self-consumptions scenarios and energy communities, cybersecurity in large PV plants, protecting energy trading AI agents, etc.)

- Identify technologies/materials to be applied to existing PV plants to improve performance (e.g. anti-reflective/anti-scratch protective coatings on glass).

KPIs

KPIs envisaged for this roadmap are:

KPI	Target Value (2030)
Components	BOS components should contribute to the general objective of making PV the most competitive energy source and achieve a LCOE of 0.025 cEUR/kWh and 0,05 cEUR/kWh for IPV
Operational LIfetime	BOS components should secure operational lifetimes of complete PV systems in the way of 50 years, similarly to PV modules or construction materials
Market and Production	BOS should be available as the core element of PV integrated PV systems, enabling the integration of PV everywhere: Low-cost adapted durable mounting structures, cabling and electrical components (e.g. PV connectors, DC switchgears, further safety components, etc.) for small or large PV systems.

Today's modern PV factories produce several gigawatts of wafers, solar cells and modules every year, and the trend is rising sharply. This equates to about one billion solar cells produced annually per factory.

Objective 3: Digitalisation of Photovoltaics

The advent of new digital technologies such as Big Data, robotics and blockchain allows for the emergence of entirely new solar business models and for the improvement of existing models, making them more profitable. Moreover, digital technologies can be used to reduce costs and increase performance at almost every point of the solar value chain, from cell and module manufacturing to Operation and Maintenance (O&M) of PV power plants.

This objective aims at introducing digital technologies to reduce cost and increase the quality of PV value chain manufacturing (roadmap 6), to increase energy yield, and to make PV technology suited for all emerging new applications and a dependable component of the energy system of the future (roadmap 7).

Roadmap 6: Digitalisation of PV manufacturing

Rationale for support

Today's modern PV factories produce several gigawatts of wafers, solar cells and modules every year, and the trend is rising sharply. This equates to about one billion solar cells produced annually per factory. During production, extremely large and high-dimensional data is generated: for example, from the production equipment and the inline measurement devices which monitor the process and classify the products. Digitization helps to collect and evaluate these large amounts of data. Production can be optimised in terms of efficiency, durability and manufacturing costs of cells and modules. Equipment manufacturers and suppliers can generate important customer benefits in the generation of machine data, the definition of interfaces, machine control and the digital optimisation of analysis and (predictive) maintenance concepts. Heatmap and experienced trend analysis can lead to manual and automated closed circle optimisations.

Status

Only partial quantities of the diverse data are centrally collected in databases and processed in a standardized manner using MES software systems (Manufacturing Execution Systems) in most factories. In addition, the data is evaluated manually, for example by means of data correlations. First factories already use wafer tracking methods, which are based on virtual tracking or active tracking. Active wafer tracking may be realised either by encoding each ingot with a slice code leading to an edge code at each wafer or by encoding each wafer by a surface code. This coding is read out with a camera before each production step, which allows the production data of the respective solar cell to be assigned. In the future, this process will make it possible to accurately record and evaluate the entirety of production data for each wafer, which can be used to establish a correlation between the efficiency and longevity data. Solar cell companies are already researching software based on artificial intelligence (AI) with which production data is evaluated to support the automatic analysis of large amounts of data and optimise production.

The fully automatic identification and quantification of the measurement data for data analysis, production control and process optimisation using modern AI is possible but not yet widely adopted. Experienced machine vision companies and R&D institutes have the expertise to develop AI methods that enable meaningful data compression and theory-based data analysis. This adds value to the existing procedures and especially enables companies producing in Europe to benefit from local support and protection of intellectual property (IP). Regarding the operation and maintenance of production machines, IT-based remote maintenance systems already exist today, but these are still used by people and are carried out according to schedules or in the event of plant malfunctions. Predictive or predicted machine maintenance is not yet state-of-the-art.

Targets, Type of Activity and TRL

Research and development for digitalisation in photovoltaics combine two megatrends and thus offer a great opportunity for our climate and the PV industry. By 2030, European Companies and research institutions will have seized the opportunity to improve cost efficiency in the manufacturing of PV cell, module, inverter, and mounting system.

Digitisation applied to manufacturing will allow maintenance intervals or failure rates of modules to be better predicted. Systematically comparing PV power plant and component quality will enable high learning effects. **The long-term vision is to evaluate and link the data from component production to the construction and operation of PV power plants.** By 2030, the first automated self-learning and self-optimising factories with very little downtime will exist.

Generated data will be stored centrally requiring standard data representations and interfaces. Workpiece tracking will link single-wafers or carriers to their particular production parameters. These will vary greatly as greater diversity in PV products is expected. Legal hurdles for gathering using and sharing and exploiting data must also be overcome.

AI-supported software algorithms will scour data volumes for new connections and correlations to optimise production. The AI software will be self-learning to handle the large volumes.

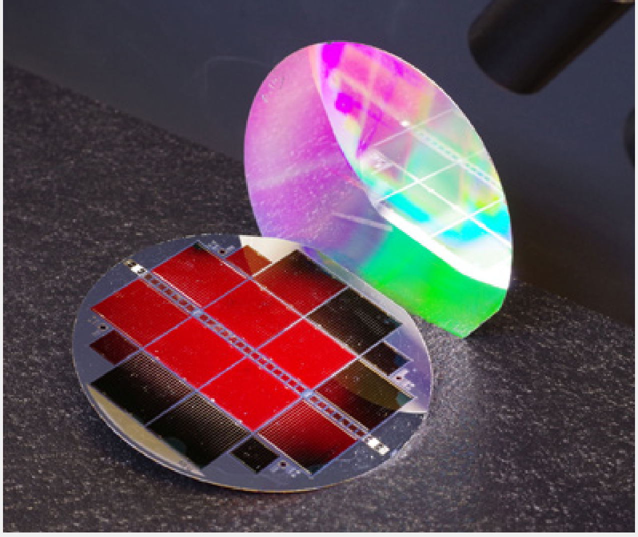
AI kits and largely standardized AI application packages illustrating sample solutions for typical AI-based machine applications will be available.

In particular for new module and cell concepts - such as multi-junction technologies, combining thin-film compound semiconductors, perovskites with silicon, recycling strategies need to be developed and findings of these developments need to be shared upstream to improve design concepts.

Regarding digitization of PV manufacturing, the following research actions are required:

» Early-Stage Research Actions (TRL2-3)

- Data generation
  - Develop intelligent, self-sufficient multi-sensors for the acquisition of relevant data and suitable application of the generated data for AI-supported control and optimisation
- Use digital twins (a digital twin is a “virtual representation of a real object or process”)
  - Develop multi-scale and meta-models of manufacturing processes, production and products as well as their components and their evaluation for optimisation of PV production through AI methods
  - Develop digital twins of the entire production as the basis of a self-learning factory (vision) to accelerate optimisation cycles through automated data analysis
- AI-based data analysis
  - Develop self-learning AI-based software that automatically analyses the large amounts of data during production, resulting in increased cell efficiency and reliability
  - Improve human-computer interaction to support the adaptation of process parameters, e.g. automatic setup of measuring systems
  - Consumable procurement triggered by the production plant



The new III-V // silicon tandem solar cell with 35.9 % efficiency. The top subcells, made of GaInP, glow red under illumination. This is a sign of outstanding material quality. The back side of the cell shimmers in rainbow colors, because a nanostructure was used on this side to increase the efficiency. © Fraunhofer ISE

» Development Research Actions (TRL 3-5)

Data generation:

- Develop virtual and active identification processes and intelligent logistics components for material and device tracking across the value chain
- Develop fast and cost-efficient in-line measurement technology for real-time process control to widen the data base for machine learning in production.

Exchange and storage of data:

- Develop a range of common and standardised databases, including cloud services, to ensure data exchange across all segments.
- Develop plant interfaces for simplified and flexible connection of production machines to the existing data infrastructure of the factory and extension for bi-directional communication for real plant control by Advanced Process Control (APC) algorithms.
- Further development of object- and graph-based databases for production control and development of processes for automated context acquisition and assignment to expand the database (including unstructured data) and improve data quality (collection of metadata) for AI-supported production optimisation individualized production environments

Digital twin

- Further development of machine modelling, specifically of parts subject to wear, to implement predictive maintenance
- Realisation of a central simulation platform, which is multi-user-ready with proprietary shares to protect core competencies for lowering barriers to data exchange
- Development of standards for simulation interfaces for significant acceleration of the adaptation of simulation modules into overarching models
- Methods for improvement of the image of digital twins to allow accurate modelling based on the precision of measurement data to improve the value of the digital twin due to increased imaging sharpness

AI-based data analysis

- Identification of relevant machine parameters that influence customer targets and development of suitable self-optimisation algorithms
- Develop AI-supported concepts for predictive maintenance

» Demonstration Actions (TRL 5-7)

Data generation:

- Use of existing system sensors for advanced process/maintenance monitoring to benefit from short-term potential for improved monitoring of solar cell production

Digital twins:

- Development of best practice examples of digital twins to visualise its benefits

Cross-Cutting topics:

- Demonstration of transfer of digitization methods to industry. For this AI kits/application packages that present the application possibilities and benefits of various AI software solutions and illustrate them with sample solutions are required. New business models for the provision of equipment such as “pay per use” or “production as a service” and reduction of investment costs of new factories/provision of production know-how by mechanical engineering companies need to be implemented.

Roadmap 7: Digitalisation of PV systems

Rationale for support

The mainstream PV industry produces cells and modules that are standard in size and shape, but are not optimised for the many emerging applications (e.g. agri-PV, floating PV, vehicle-integrated PV, ...) and do not deliver maximal potential electricity when shaded, a common situation in urban areas and indoor spaces. To fully harvest all available solar energy and to extend the variety of PV applications (towards “PV everywhere”), so-called digital PV-modules need to be developed. The combination of PV and various digital technologies can provide virtual inertia, support the grid and smooth the output of systems (e.g. by very accurate solar energy forecast and energy storage at the level of the PV module or system).

Status

At present, most PV modules fulfil only one function, namely electricity generation, and therefore they usually contain only simple electrical actuators such as power optimisers.

Field uptake of techniques for production forecasting (foremost among them operation and maintenance optimisation, and sizing) is still limited, with TRL in the range 7-8 for forecasting applications and 3-4 for energy trading agents.

Application of AI to PV modeling and sizing relies on blackbox models while recent findings suggest that integration of physical (“whitebox”) modeling (and AI will significantly increase accuracy. Work targets c-Si technology.

Forecasting algorithms are mostly developed for short term horizons (up to 48hrs), often relying on well-established machine learning and system control methodologies with limited uptake of deep learning methodology. Most AI-based models have shown to perform well for sunny days, while for cloudy days the forecasting accuracy decreases significantly.[(33)] and are usually limited to local predictions.[(34)] No accurate general regional model has been proposed to date.[(35)] EU research groups are among the most active in the forecasting field, foremost among them Italian and Spanish groups who produce 35 % of the world’s publications on machine learning for PV forecasting (China: 23 %; US: 13 %).[(36)]

AI in production optimisation is currently mostly based on MPPT or solar tracking.

PV plants are complex systems and fault sources are multiple, including optical degradation or fault, electrical mismatches (including shading), potential induced degradation (PID), defective/short-circuited bypass diodes, short-circuited modules or strings, and junction box failure. Most research work on AI advanced maintenance, however, operates on single fault detection with fault classification accuracy rapidly decreasing with the number of considered classes and detected faults are not precisely localized. Human investigation is needed. Aerial inspection with IR Cameras and artificial vision components equipped UAVs can improve the fault localization but has been little tested in the field.

Targets, Type of Activity and TRL

Novel digital PV-systems will be developed combing PV technology with photonics, micro- and power-electronics, sensors technology, energy storage, wireless communication, and computer science.

AI and Big Data for PV techniques are essentially in their development phase having been tested on a limited scale in the field and mostly as an off-line data processing tool. The main step to be taken is to favor their actual implementation as a real time field deployed asset. The ongoing setting up of large-scale PV plant data collection, monitoring and performance analysis will contribute, through semantic extraction capability of Big Data techniques, to enlarging the knowledge about real time and long-term behavior of PV installations. As an enabler, IoT technology is expected to play a major role in increasing the availability of real time data streams for monitoring and diagnosis of PV plants, particularly in remote locations.

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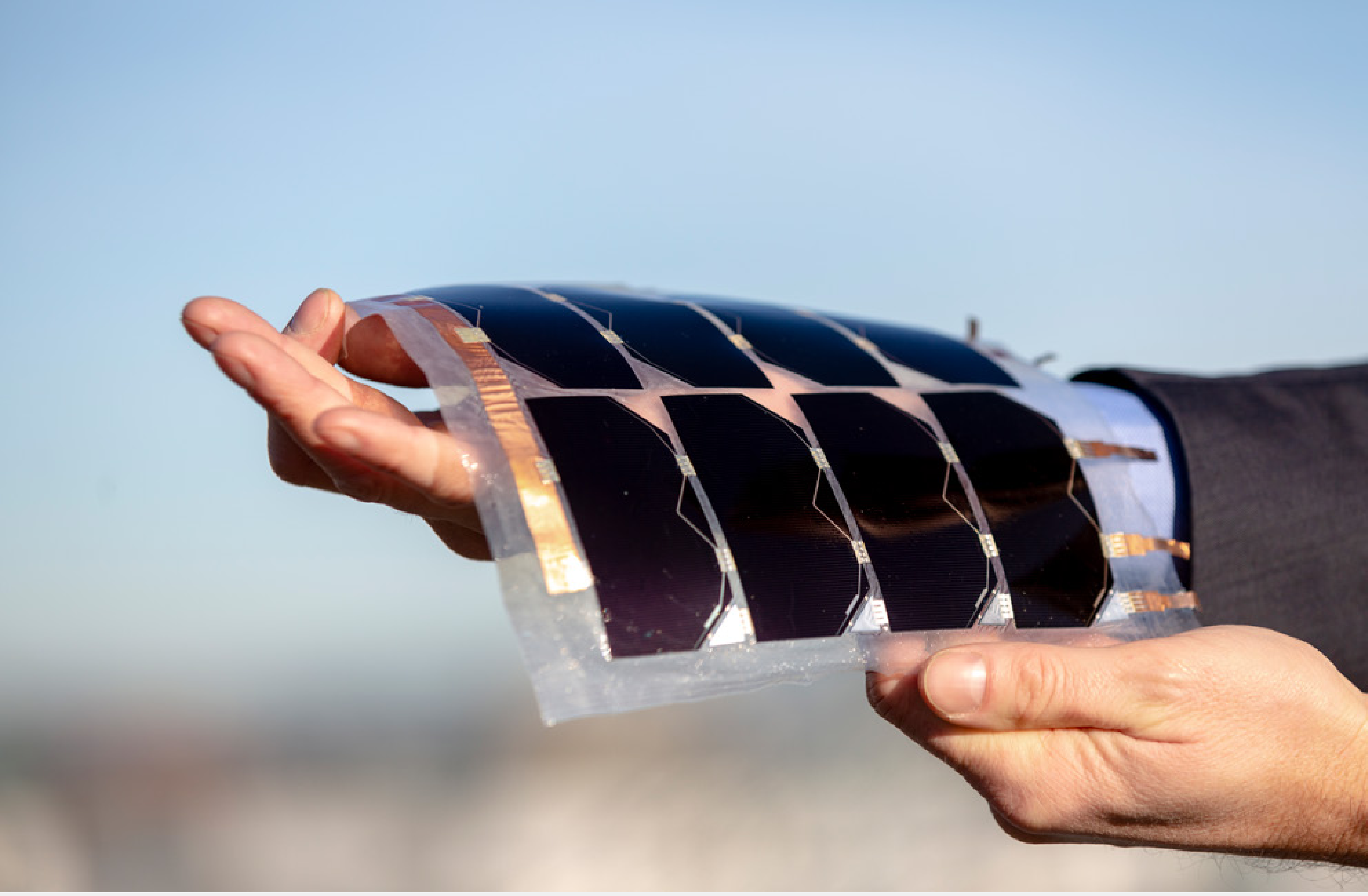
(33) Mellit, Massi Pavan, Ogliari, Leva, & Lughi, 2020
(34) S. Pelland, 2013
(35) Mellit, Massi Pavan, Ogliari, Leva, & Lughi, 2020
(36) Ibid.



Ultra leight PV module with high efficiency. GaInP/GaInAs/Ge triple-junction solar cells. © Fraunhofer ISE

Digitalisation of PV modules themselves will improve data collection, widening the range of available parameters and helping the development of advanced AI4PV technologies which in turn represent a significant opportunity for:

- Modeling of Energy Yield and Sizing (Wu, 2020) (Ghannam R., 2019) (Hesan Ziar, 2021) (A. Mellit, 2009)
- Development and optimisation of PV modules production (Ghannam R., 2019) (Project SelFab Website, 2021)
- Operational Optimisation (e.g. MPPT) and Yield Forecasting also in the context of energy communities
- Extending Life and Long-term Yield maximization: Fault detection & Predictive Maintenance (Muhammad Hussain)
- Fast Energy trading

The expected increase in cell and module technologies field readiness will increase the needs and hopefully the development of custom energy yield modeling and prediction of site suitability in urban scenarios. To accelerate the integration of PV in urban environments at large scale, we need to improve methods to predict surfaces (mostly roofs) potential yield for different cells and modules PV technologies including bifacial modules.

Following the increase in the digitalisation of PV modules and sensors integration it is expected that AI can play a significant role in automating the PV module operational optimisation. An embedded AI can improve efficiency by adapting MPP to shading and temperature.

Fault diagnosis algorithms will be better at multi-fault identification, and at isolating the contribution of each to underperformance, e.g. Particulate and Ozone (Fattoruso et al., 2020) or shading (Johnson, 2021).

By 2030, AI will be capable for accurate forecasts in cloudy weather and for time horizons beyond 72hrs. Deep learning algorithms fed with air temperature, solar irradiance, relative humidity, wind speed, and/or remote sensing data (e.g. cloud cover) will be capable of regional scale forecasting.

» Early-Stage Research Actions (TRL2-3):

- Investigate whether LiFi is a technology for passing info around a PV plant.
- Modeling performances under realistic conditions to identify materials and bandgaps adapted to specific realistic conditions.

Bifacial EyeCon concentrator module for the conversion of direct and diffuse solar irradiation. © Fraunhofer ISE

» Development Research Actions (TRL 3-5):

- Integrate multi-aspect sensing (optical, thermal, electrical) into a PV module to suppress degradation, detect unwanted operating conditions and avoid failures.
- Digitalisation of PV modules: integrated sensors (optical, electronic), self-diagnosis, reconfigurable modules, self-cleaning, self-cooling with emphasis on achieving high MWh/W_p (shade tolerant; more advanced electronic design with in-module components).
- Develop wireless power transmission of electricity directly from a PV module to the energy system for additional saving on energy losses, potentially in combination with maximum power point tracking.
- Develop and apply edge AI and Big Data to:
  - improve the energy yield (advanced module control, self-reconfigurable topologies, etc.)
  - improve module and plant models
  - improve yield forecasting (deep black box model, data driven white box models)
  - implement predictive maintenance and early detection of failures in PV technologies (digital twin)
  - enable AI agents-based energy trading at plant level, taking care of specific climates /applications / conditions (snow, dust, environmental pollution, water…)

» Demonstration Actions (TRL 5-7):

- Improved and more accurate ways of creating a digital twin of a PV system or energy system to predict the output and utilization of real distributed PV technology
- Build large (time and scale dimension), wide (including not only yield but multisensorial operational, thermal, mechanical and environmental data) and possibly publicly available datasets to enable, foster and empower research in AI for Digital PV at EU scale.
- Demonstrate PV modules with integrated storage (e.g. solid state batteries) and new energy management systems for coupled PV-battery systems.
- Demonstrate automated and predictive PV asset management software based on sensor-data-image fusion to reduce human effort and increase trustworthiness of current PV asset management software.
- Improved energy yield prediction and forecasting software based on physical models (“whitebox models”) that can provide more accurate and faster predictions on very short timescale.

CHALLENGE 2

Lifetime, Reliability and Sustainability Enhancements (through Advanced Photovoltaic Technologies, Manufacturing and Applications)

PV modules and systems must reliably generate TWh of electricity for decades. It is also important to minimise any negative environment impacts from their manufacture. The introduction of novel technologies and novel PV system design makes the need of increased field performance and reliability a continuous industry demand.

Solutions and services which are already available in the market or close to the market will need to be continuously updated and redefined to capture innovation trends. Moreover, new technologies can introduce new degradation modes once in the field.

The production, operation, and disposal of any product carries with it an environmental burden. The minimization of the environmental burden for the whole lifetime requires the selection of materials that create fewer toxic by-products, allow a longer life, are more recyclable, are lighter, less energy intensive in production, and need fewer scarce resources._

In line with the material efficiency hierarchy, resources should be kept in productive use as long as possible and at the highest quality possible. A license to operate a PV plant should be needed, one that guarantees materials will be recovered at the end of its life.

This Challenge is divided into two objectives:

- Objective 1: **Sustainable and Circular PV**
- Objective 2: **Reliable and Bankable PV**

Together, these objectives cover all aspects that need to be improved to enhance the lifetime, reliability, and sustainability of PV technology.

From multi-MW utility scale down to small systems on residential roofs, electricity generated by photovoltaic systems is changing the energy landscape as we know it. GWs of capacity are added worldwide year after year where the cumulative 1 TW goal could be achieved already in 2022. By the end of the next decade the TW annual market could become reality. PV already represents a share of more than 8 % of the electricity generation in some countries (Italy, Germany, Greece, to name a few) and with these values in mind the penetration levels will quickly reach the double-digit all-over Europe. It is within this scenario that the PV sector must ensure that the installed power capacity in GW can also reliably generate TWh of electricity for an extended lifetime. With PV becoming mainstream, it becomes also important to ensure sustainability from energy, environmental and investment viewpoint.

← PV-TEC Front End: Inline etching tool for ozone based wafer cleaning and single side rear emitter removal.
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Objective 1: Sustainable and Circular solar PV

Solar photovoltaic (PV) technology is one of the key engines powering the energy transition. An important reason for PV's large role in the energy transition is its perception as a renewable and sustainable energy technology with a low environmental impact.

However, it remains clear that production, transport, installation and operation of PV systems all require the consumption of materials and energy, which has an environmental impact. We install PV to drastically reduce the high emissions of greenhouse gases associated with our largely fossil fuel-based current energy system. Although PV has a relatively small environmental impact per unit of electricity generated, the huge role that PV needs to play in the energy transition implies that enormous amounts of energy and materials must be consumed for its manufacturing. This gives rise to two key issues to be addressed by R&I efforts. First, the environmental impact of manufacturing PV systems must be (further) minimized. Secondly, as the numbers of PV systems on the market rise, resource efficiency is becoming an increasingly critical factor for the long-term success of the sector. For a truly sustainable transition towards a low-carbon future, renewable energy technology must be close to 100% recyclable and leanly manufactured, i.e. circular.

The R-ladder of Circularity Strategies

In this objective, we discuss the sustainability and circularity of PV using the R-ladder of circularity strategies. There are six distinct strategies towards circularity: Refuse and Rethink, Reduce, Reuse, Repair and Refurbish, Recycle, and Recover.[37] Each of these steps would serve to (further) reduce key issues regarding the sustainability of PV: greenhouse gas emissions and other environmental impacts as well as material and resource availability. Here, we apply these strategies along the PV value chain, both to define key current issues, as well as to suggest specific research activities.

Evaluating the sustainability and environmental impact of PV

The production, operation, and disposal of any product carry with it an environmental burden. The minimization of the environmental burden for the whole lifetime requires the selection of materials that create fewer toxic by-products, allow a longer life, are more easily recycled, are lighter and less energy intensive, and that, where possible, reduce the net demand of scarce resources, where proof of concept of industrially feasible devices with alternative materials must be approached.

Any negative environmental impact associated with the life cycle of PV systems must be minimized. Environmental impacts of products and services are commonly determined using Lifecycle Assessment (LCA), an ISO standardised method that builds an inventory of all material and energy flows required for the product, and consequently applies a set of methods to determine the environmental impact of the product in a multitude of impact categories. An important concept in LCA studies is the *functional unit*, which identifies the function of the product under study. As the function of PV is to produce electricity, the environmental impact is commonly expressed for the functional unit of a kWh of electricity produced (or delivered to the grid).

Currently, LCA studies that aim to identify the environmental burden associated with electricity from PV systems, commonly focus on estimation of the carbon footprint of PV electricity, and cumulative energy demand (CED) and associated energy payback time (EPBT) of PV systems. Additionally, researchers often use the term energy return on energy invested (ERoEI) to relate the cumulative energy demand to the lifetime energy yield of PV systems.

The carbon footprint is a measure which can be used to compare electricity from PV to that from other sources and is expressed in gCO_2-eq/kWh. Here, one kWh is the functional unit. As PV electricity has no direct point-of-generation emissions, a large share of the carbon-footprint of PV results from the direct and indirect energy use during manufacturing, and smaller parts are associated with transport, installation, operation, and other parts of the value chain.

EPBT refers to the amount of time necessary to generate an amount of electricity equivalent to the amount of primary energy (PE) invested during manufacturing. ERoEI provides the ratio between produced and invested energy, similar to the related financial parameter RoI. $ERoEI_{el}$ refers to the ratio between produced electricity and pri-

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(37) Groot, T. And Kishna, M., 2019. Outline of the circular economy. PBL Netherlands Environmental Assessment.

For a truly sustainable transition towards a low-carbon future, renewable energy technology must be close to 100 % recyclable and leanly manufactured.

mary energy investments, while $EROEI_{pe}$ relates to the ratio between equivalent primary energy output and primary energy inputs.

When discussing carbon footprint, EPBT and ERoEI of PV systems, there are several key considerations to take note of. First, for all these environmental impact parameters, there are a set of assumptions that strongly affect their final values:

- Production location: for a very substantial part, the environmental impact of PV systems and the electricity they generate results from the consumption of electricity in direct and indirect manufacturing processes. LCA studies often assume systems are produced using the average electricity mix of the manufacturing country. As such, current LCA's assume production in China, which has an electricity mix with large shares of coal.

- Installation location: the installation location determines both the annual irradiance and thus annual system yield, as well as the efficiency of the local grid. The efficiency of the local grid is the ratio kWh_{el}/kWh_{PE} at the point of deployment, and thus shows the efficiency of converting primary energy into electricity. The conversion to and from primary energy is required to calculate EPBT and ERoEI, as for these metrics all embodied energy is considered, and primary energy is a common metric to account for all forms of input energy. However, is very sensitive to the penetration of renewables in the grid, as they have a very high efficiency from primary energy to electricity. High grid efficiencies thus mean that the energy payback time will be higher. This also has its effect on the ERoEI values. As an example, Fthenakis and Leccisi [38] show that, when increases to a value of 0.7 (which is the estimated in California in 2030 with a penetration of renewables of 80 %) the $EROEI_{PE}$ drops from around 50 currently, to just over 20 in this 2030 scenario.

- Performance Ratio: the performance ratio PR determines the annual electricity yield, and as such affects all environmental impact parameters. The current standard for PR, assumed in LCA studies, is 85 %.

- System lifetime: ERoEI and carbon footprint both rely on the lifetime electricity yield from PV systems. Typically, a system lifetime of 30 years is assumed, commonly with one replacement of the inverter.

Finally, it should be noted that it is recommended by the European Commission to follow the Product Environmental Footprint Category Rules (PEFCR) when conducting an analysis of the environmental impact of PV. These PEFCR include a broad set of environmental impact categories. Although as said above the focus of PV LCA is commonly on greenhouse gas emissions and energy demand, R&I on sustainable and circular PV should include all those impact categories. Many of the R-ladder strategies will reduce the environmental impact in multiple or all categories.

(38) Fthenakis and Leccisi (2021), Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends, https://doi.org/10.1002/pip.3441

Roadmap 1: Refuse and Rethink, Reduce (Low environmental impact materials, products, and processes)

Rationale for support

To identify the main areas of improvement for the environmental footprint of PV, it is necessary to regard the technology's entire lifecycle. Using LCA, important knowledge can be gained as to which processes and materials contribute most to the overall environmental footprint, and as such are key candidates in the first R-ladder strategies: Refuse/Rethink and Reduce.

For the strategy *Refuse and Rethink*, a good example would be the development of lead-free solder, avoiding the use of toxic components and their possible release to the environment, and hence lowering the environmental impact in toxicity-related impact categories. LCA should ideally be applied early in the development of a technology, so that high-impact materials or processes are avoided when possible.

The lifecycle thinking also aids in identifying key candidates for the strategy *Reduce*. Although it seems self-explanatory that reductions in material use lead to improved environmental impact, it is of course essential that these reductions do not adversely affect the function of the technology.

Status

State of the art PV LCA studies use life-cycle inventory data from 2020, assume manufacturing of PV in China, and module efficiencies of 20.5 % for mono- and 18 % for polycrystalline based PV systems. These systems, when transported to and installed in a region of moderate insolation (1700 kWh m^{-2} yr^{-1}) have a carbon footprint of 23 to 25 gCO_2-eq/kWh, respectively.[41] The EPBT of these systems is around 0.8 years, while the $ERoEI_{el}$ are 11.5 and 10.5 and $ERoEI_{pe}$ are 38 and 35, respectively. Summarizing the latest state-of-the-art in LCA of PV, we can see:

- Typical system energy payback time Southern Europe is around 0.8 years[41]. The long-term potential is 0.25 years [(39)]
- Solar grade silicon consumption: 3 g/W (2020) [41, (40)], target <2 g/W in 2025-2035 and beyond (SRA PV, 2011)
- non-cell general material intensity in 2018 (t/MW) (modules and BOS) [(41)]
  - Concrete (system support structures): 60.7
  - Steel (system support structures): 67.9
  - Plastic (environmental protection): 8.6
  - Glass (substrates, module encapsulation): 46.4
  - Al (module frames, racking, supports): 7.5
  - Cu (wiring, cabling, earthing, inverters, transformers, PV cell ribbons): 4.6
- Typical carbon footprint of a mono-Si PV ground-mounted system in Southern European insolation, 1700 kWh/m²/yr, performance ratio of 0.85, and lifetime of 30 years: 23-32 gCO_2-eq/kWh [41, (42)]
- Estimates for carbon footprints of thin film technologies from a screening and harmonization study[(43)]: 20, 14, and 26 g CO_2-eq/kWh, respectively, for a-Si, CdTe, and CIGS, for ground-mount application under southwestern United States (US-SW) irradiation of 2,400 kilowatt-hours per square meter per year (kWh/m²/yr), a performance ratio of 0.8, and a lifetime of 30 years. Harmonization for

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(39) A Strategic Research Agenda for Photovoltaic Solar Energy Technology. Edition 2. 2011

(40) Bernreuter Research. Polysilicon market analysis. 2020

(41) Joel Jean, Patrick R. Brown, Robert L. Jaffe, Tonio Buonassisi and Vladimir Bulović. Pathways for solar photovoltaics. Energy Environ. Sci., 2015,8, 1200-1219

(42) Friedrich et al, 2021. (submitted)

(43) Kim, H.C., Fthenakis, V., Choi, J.-K. and Turney, D.E. (2012), Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation. Journal of Industrial Ecology, 16: S110-S121

the rooftop PV systems with a performance ratio of 0.75 and the same irradiation resulted in carbon footprint estimates of 21, 14, and 27 g CO_2-eq/kWh, respectively, for the three technologies.

- The lack of studies and poor details on the environmental performance of available processes for indium recovery from obsolete flat panel displays, semiconductors, and similar products leaves uncertain if EoL recycling of indium would actually result in net environmental benefits [(44)].

- China's position as the key player along the solar PV supply chain (in raw materials, processed materials, components, and assemblies) creates the potential for supply risks and bottlenecks[(45)]

Across the board, these latest results show a strong decrease in carbon footprint compared to those using 2015 data. Key drivers here are:

- Silicon production and material use efficiency
  - Thinner wafers
  - Diamond wire wafering with much reduced kerf losses
  - Reduced electricity consumption along the value chain
- Improved cell and module efficiency

Continuous technological improvements like these have resulted in a strong decline of the environmental impact of PV technology over the past decades. Due to improvements in material use (e.g. the amount of silicon in g/W_P) and improved module efficiency, both EPBT and carbon footprint have dropped by roughly an order of magnitude in the past 30 years.[(46)] This indicates a *learning rate* of around 12 % for CED of PV systems, and of 16.5-23.6 % for carbon footprint, depending on the type of system.

For a renewable energy technology to be successful, it needs to strongly reduce the carbon footprint of the sources it will replace, while having a strong net positive energy balance. This implies that the energy payback time of systems needs to be short, the carbon footprint needs to be reduced, the use of local materials to reduce transport costs in systems must be increased, the use of hazardous materials needs to be avoided, and systems and system components need to be designed in a way that encourages recycling and decreases material usage.

While the current environmental impacts of PV electricity are very much (up to several orders of magnitude, depending on the impact parameters considered) smaller than those of incumbent (fossil fuel based) sources, the vast scale of projected PV deployments in the energy transition requires that the technology keeps improving the technology, and, as Roadmap 5 also says, a harmonization and update of life cycle inventory databases is required to cope with this fast development of PV technologies and integrated applications (BIPV, VIPV, AgriPV, FloatingPV, IIPV, etc.), so that accurate LCAs may be performed now and in the future.

Low environmental impact through dedicated life cycle engineering, focusing on low embodied carbon materials and low-carbon electricity for energy intensive manufacturing steps - thereby reducing energy payback time and carbon footprint / global warming potential of PV should be complemented with the incorporation of scope 3 emissions (related to the embodied carbon of the supplied system components) in public renewable energy tenders and commercial PPAs, with this a legal requirement if possible.

Targets, Type of Activity and TRL

Continuous improvements of PV technology are required for future success. Even incorporating steady learning rates, and thus continuous improvement of PV technology with reducing environmental impacts, up to 11 % of the remaining carbon budget needs to be used to install sufficient quantities of PV.[(47)] Thus, it is clear that PV technology needs to keep improving over the entire value chain.

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(44) Ciacci, L., Werner, T.T., Vassura, I. and Passarini, F. (2019), Backlighting the European Indium Recycling Potentials. Journal of Industrial Ecology, 23: 426-437. https://doi.org/10.1111/jiec.12744

(45) "European Commission, Critical materials for strategic technologies and sectors in the EU- a foresight study, 2020"

(46) Louwen, A. Nature Communications **volume 7**, Article 13728(2016)

(47) Goldschmidt, Jan Christoph and Wagner, Lukas and Pietzcker, Robert and Friedrich, Lorenz, 2021. Technological learning for resource efficient terawatt scale photovoltaics, ***Energy Environ. Sci.*** 14(10), pp.5147-5160, http://dx.doi.org/10.1039/D1EE02497C

Drone thermography. © Above Surveying

Although the environmental impact of PV electricity is typically assessed using metrics focusing on energy demand (EPBT) and greenhouse gases (carbon footprint), recent studies have been starting to focus more and more on the material constraints of the PV industry. The expected enormous growth of the PV industry, could result in it becoming the major consumer of several materials, including flat glass and silver. Furthermore, the consumption of aluminium for PV module frames results in high energy demand and associated carbon emissions, as well as posing possible constraints.

- Early-Stage Research Actions (TRL 2-3)
  - Analysis of the evolution of the carbon footprint over the years (from 40-100 g CO_2-eq/kWh towards lower values) [48] for PV modules and systems with a clear definition of the boundaries of the calculation
  - Determine the environmental benefits of recycling precious metals
- Development Research Actions (TRL 3-5)
  - c-Si PV module BOM without harmful substances (Pb, F etc.) but without limitation in terms of quality and reliability
- Demonstration Actions (TRL 5-7)
  - Development of Cu-based contact systems
  - Use of recyclable polymers (PET, PP, PE, etc.)
- Flagship Action (TRL 7-8)
  - Reduced kerf loss in sawing
  - Favour the consumption of raw material produced in Europe, for example [[49]]:
    - Silver produced in Poland is about 20 % of global production share, together with Peru and Australia
    - Silicon produced in Norway (6 % of global production)
  - Analysing the historical development of key PV technology and designs to aid in setting KPI targets for 2030 and beyond
    - Using experience curves and prospective market developments to estimate the improvement of key design parameters (efficiency, wafer thickness, etc)
    - Modelling the environmental impact using these values and future estimates of electricity grid mixes

(48) Louwen, A. Nature Communications **volume 7**, Article number: 13728(2016)
(49) U.S. Geological Survey, 2020, Mineral commodity summaries 2020. https://doi.org/10.3133/mcs2020.

Digitalisation can be used to track the resources needed for a PV project or service.

The role of digitalisation

Although an LCA is an environmental approach which brings a global vision of environmental impacts of a service or a product, the incorporation of LCA in companies is most of the time slow and costly. Digitalisation offers the opportunity to both improve on this time-consuming process, as well as to improve the availability, quality of data and to ensure it is up to date.

1. Flexible data update [[50]]:

1.1 Challenge: it takes a lot of time and energy for LCA experts to gather the data needed in order to produce a complete and reliable analysis of a product (life cycle inventory). One of the reasons why reliable data is difficult to find for LCA experts is that the information among an organisation is hard to find, either because it can be "lost" among this organisation or it isn't transmitted well from one service to another.

1.2 Opportunities:

a. Digital cooperation on an international platform to help in creating a data commons. Data commons also decrease the workload of requesting each individual organization for data by making legitimate data open.

b. LCA could be associated with Computed-Aided Design (CAD) software. Thus, LCA would be linked to the value chain of the company: some data entered into the CAD software would be reused into LCA thanks to an Application Programming Interface. Or LCA could be a plug-in added to a CAD software. Data would thus be visualised directly through the CAD software:

   – The amounts of materials used for the product designed would be more easily found because they will be directly integrated into the model designed. The environmental impact calculation would intervene at the beginning of the design process;

   – The visualisation of the product itself could be interesting so LCA experts could easily see if some data is missing: the drawing of the product could change its colours if the data corresponding has been entered into the LCA analysis.

c. Modular, flexible and transparent LCA software: LCA software, no matter to which categories they belong to, are seen as too inflexible in their processes. This could be explained by the lack of open-source software competitiveness. A modular software can be thus a solution to avoid cognitive overloading and calculations issues. Such a software could be developed as independent bricks. Designing a scalable LCA software could help small and medium sized companies (SME) to adapt to environmental norms, especially companies who don't have the financial capital for an LCA expertise. Some questions remain unsolved. For example: How modular an LCA software should be developed? Can a LCA software be compatible with Industrial Ecology (IE) or Material Flow Analysis (MFA) tools? Those issues should be tackled in future research.

2. Validation of LCA results: the validation of an LCA is the assurance that the model matches the actual system identified. Currently, the validation phase is seen more as an "additional" phase of an already well-established tool. However, LCA lacks empirical validation. Perhaps the digital transformation would allow the development of techniques capable of confirming or invalidating the results of LCA models in reality. This would allow LCA to be further linked into concrete experiences.

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(50) Lou Grimal, Nadège Troussier, Ines Di Loreto. Digital transformation as an opportunity for life cycle assessment. *16ème Colloque National S-mart*, Apr 2019, Les Karellis, France. hal-02431651

KPIs

Process/technical KPIs	Target Value (2030)	Current value	
Energy required to produce MGS	< 8 kWh/kg	11 kWh/kg[2]	
Electricity for SoG silicon	<10 kWh/kg for advanced processes	49 kWh/kg[2]	
Electricity for Cz ingot	< 25 kWh/kg	32 kWh/kg[2]	
Wafer thickness	150-160 µm depending on wafer size [51]	170 µm[2,12]	
Kerf losses	< 50 µm[12]	60-65 µm[2,12]	
Primary raw material usage for BOS i.e., concrete and steel	Reduction by at least 3 % (4 % reduction by 2030 and further 6-7 % by 2050)		
Primary raw material usage	Reduction of Plastic, glass, Al, and Cu, by at least 3 % (respectively 3 %, 4 %, 4 %, 2 % reduction by 2030 and further 7 %, 6 %, 6 %, 7 % by 2050)		
Acquisition of PV materials from European producers	Increase silicon metal by 20 % (Norway, 6 % global share in 2019), and silver by 30 % (Poland, 20 % global share in 2019)		
Environmental KPIs	*PV system in S. Europe: 1700 kWh/m^2*	*PV system in N. Europe: 1000 kWh/m^2*	*PV system in S. Europe: 1700 kWh/m^2*
Carbon footprint Values for 2030 are based on current production electricity mixes. As the energy transition evolves, EU mix gradually moves toward Norway's electricity mix emissions.	Mono-c-Si: <18 gCO_2-eq/kWh (CN) <10 gCO_2-eq/kWh (EU) <7 gCO_2-eq/kWh (NO) Perovskite-Si tandem: <16 gCO_2-eq/kWh (CN) <9 gCO_2-eq/kWh (EU) <6 gCO_2-eq/kWh (NO) Thin film, single junction: <12 gCO_2-eq/kWh (CN)	Mono-c-Si: <30 gCO_2-eq/kWh (CN) <16 gCO_2-eq/kWh (EU) <12 gCO_2-eq/kWh (NO) Perovskite-Si tandem: <27 gCO_2-eq/kWh (CN) <15 gCO_2-eq/kWh (EU) <10 gCO_2-eq/kWh (NO) Thin film, single junction: <20 gCO_2-eq/kWh (CN)	IEA PVPS Task 12+ecoinvent+prod. China: [52] Mono-Si 20.5 %: 23 gCO_2-eq/kWh Multi-Si 18 %: 25 gCO_2-eq/kWh Monocrystalline silicon (PERC), harmonized to Southern Europe, input data from: [53] 28 gCO_2-eq/kWh (production China) 15 gCO_2-eq/kWh (production EU) 11 gCO_2-eq/kWh (production Norway) Thin film, single junction: 15-20 gCO_2-eq/kWh

(51) ITRPV 2021 for year 2031.

(52) Fthenakis, V, Leccisi, E. Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends. *Prog Photovolt Res Appl.* 2021; 29(10): 1068– 1077. https://doi.org/10.1002/pip.3441

(53) Müller A, Friedrich L, Reichel C, Herceg S, Mittag M, Neuhaus DH. A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory. Solar Energy Materials and Solar Cells. 2021 Sep 15;230:111277. https://doi.org/10.1016/j.solmat.2021.111277

Process/technical KPIs	Target Value (2030)	Current value	
CED (MJ/W_p)	<9.5 MJ/W_p mono		IEA PVPS Task 12+ecoinvent+prod. China:[52] Mono 20.5 %: 13.6 MJ/W_p mono Multi 18 %: 14.8 MJ/W_p multi
EPBT	<0.55 years	<0.93 years	IEA PVPS Task 12+ecoinvent+prod. China:[52] Mono 20.5 %: 13.6 MJ/W_p mono Multi 18 %: 14.8 MJ/W_p multi
EROI electricity kWh_{el}/kWh_{PE}	>16	>10	IEA PVPS Task 12+ecoinvent+prod. China:[52] Mono-Si 20.5 %: 11.5 Multi-Si 18 %: 10.5
EROI primary energy kWh_{PE}/kWh_{PE} =0.3	>54	>32	IEA PVPS Task 12+ecoinvent+prod. China:[52] Mono-Si 20.5 %: 38 Multi-Si 18 %: 35

Roadmap 2: Reuse, Repair and Refurbish (Designs, Systems and O&M for reuse)

Rationale for support

Recycling is the default strategy today for decommissioned PV modules in Europe. However, in the next 10-15 years it is estimated that up to 80 % of the PV "waste" stream consists of products with premature failures (IRENA/IEA-PVPS, 2016), such as production defects or damages from transportation and installation, instead of products reaching the end of their designed technical life. H2020 CIRCUSOL [54] estimated that about 2/3 of these PV modules can be repaired or refurbished. Therefore, about 50 % of the PV "waste" can be diverted from the recycling path. In reality, the ratio is likely to be even higher since decommissioned functional PV modules currently also enter the "waste" stream.

Reuse, repair and refurbish remain rather informal in the PV industry today. These activities are currently performed by independent private companies, without any support from the original manufacturers. There are currently hardly any regulations or standards on the testing, certification and labelling. In addition to this, cost related to reliability and safety testing for PV module re-use could hinder any emerging business model.

The Terawatt Era of PV modules is approaching fast, and it is raising important questions about end-of-life management as 8 million tons of PV waste by 2030 is projected by latest studies. Based to the latest available (2019) figures reported on the growth of PV installations, [55] we can estimate that about 1-1.2 million PV modules are installed every day around the world. With this in mind, and with an average annual failure rate of 0.2 % in the field, [56] we may anticipate approximately 8 million PV modules to fail every year, corresponding to an annual weight of 144 kt of potential PV waste from PV failures only. Adding also other PV waste sources and streams, such as the decommissioning of PV modules due to end of service lifetime, repowering, insurance/contractual claims, etc., the cumulative PV waste is expected to reach up to 8 Mt by 2030. [57] PV systems installed in the 2010s in the first big wave of solar technology are coming to an end. Hence, a major PV repowering wave is starting in Western EU countries. This means that well-functioning 10-15 years old PV modules are replaced in utility-scale PV power plants.

Status

Latest research on the potential of circular economy in the PV sector indicates that 45 %-65 % of decommissioned PV modules with occurred failures can be, in principle, repaired/refurbished and reused, thus being diverted from today's default "linear" path that leads to simple disposal or (at best case) partial recycling of such PV modules. [58] This strategy is also beneficial for Roadmap 1 as in fact reduces the use of raw materials as it extends PV module useful lifetime. Through the CIRCUSOL project, researchers have identified that several failures can be repaired or mitigated already in an economically viable way – particularly junction box and bypass diode failures, potential induced degradation (PID), defective frames and some types of backsheet defects and soiling-induced hot spots. On this basis, three key factors-metrics are identified today as indispensable to assess and justify the technical/economic bankability of PV reuse business:

- The addressable volume (linked to market profitability)
- The second-life product reliability and remaining efficiency certificate (linked to market confidence)
- Reuse and repair integration in the current PV value chain

Embracing a circular economic model for this maturing industry brings a major opportunity to ensure that PV becomes one of the most sustainable sources of energy. In the circular economy approach reuse and repair actions are playing a core role to prolong the useful life of PV modules avoiding their early entry in the waste stream. Additionally,

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(54) https://www.circusol.eu/en
(55) IEA-PVPS-report "Snapshot of Global PV Markets 2020"
(56) M. Köntges et al. (2017). Assessment of Photovoltaic Module Failures in the Field. Report IEA-PVPS T13-09:2017. M. Köntges et al. (2014).Review of Failures of Photovoltaic Modules, Report IEA-PVPS T13-01:2014.
(57) Weckend, S., Wade, A., Heath, G. (2016). End-of-life management: Solar Photovoltaic Panels. Report IRENA & IEA-PVPS T12-06:2016 © IRENA and © IEA-PVPS
(58) Circular Business Models for the Solar Power Industry" (CIRCUSOL); H2020-EU.3.5.4. [https://www.circusol.eu/en].

replacement of damaged PV modules produced > 5 years ago by new ones becomes increasingly difficult due to swiftly changing PV modules sizes and properties. Re-used or repaired PV modules could serve as a source of spare parts for PV systems, prolonging those systems' operation.

The modules installed in the PV installation boom of 15 years ago are starting to be decommissioned. Re-use of PV modules is a nascent sector with companies operating in an uncharted and mostly unregulated domain. The PV re-use market is growing with approximately 15 companies worldwide moving around 500-600 MW_p (or 40000 tons) of PV modules yearly including 200 MW_p/year in Europe.

Targets, Type of Activity and TRL

Materials

» Development Research Actions (TRL 3-5)

- Reversible materials aiming to reduce recycling costs (elements in the module permitting an easier and cheaper recyclability)
- Novel generation of PV front and backsheet materials, coatings designed for re-use (by 2025)

» Demonstration Actions (TRL 5-7)

- Front and backsheet, glass repair materials and technologies with broad range compatibility between material types validated through laboratory and field tests
- Design, develop and validate non-destructive characterisation techniques for rapid assessment of the state-of-health of PV module front and back sheets coatings, packaging materials and assess possible material (in) compatibilities
- PV interconnection materials and technologies with self-healing and/or resiliency to failure properties
- Novel generation of PV front and backsheet materials, coatings designed for re-use validated in accelerated reliability testing and outdoor test facilities (by 2028)

» Flagship Actions (TRL 7-8)

- Novel generation of PV front and backsheet materials, coatings designed for re-use validated in accelerated reliability testing and outdoor test facilities and integrated in industrial manufacturing lines (TRL8-9) (by 2030)

Technology

» Demonstration Actions (TRL 5-7)

- Detailed technical solutions for PV module repair of outer packaging layers, electrical connections, delamination validated with extensive accelerated and outdoor reliability testing
- Develop in-depth insights in reversible failure mechanisms and devise field curing methods (e.g. PID, LeTID, etc.)

» Flagship Actions (TRL 7-8)

- Deployment of repair technology solutions in up-scaled and semi-automated remanufacturing lines
- Introduction, qualification and industrialization/upscaling of PV module (and system) designs with higher degree of repairability and/or modularity (which in turn facilitates repairability) and re-use. Dedicated solutions are needed for (mass) customised products.
- Develop automated and /or field-testing methods for quality assessment for re-use PV modules state-of-health, performance, safety assessment and sorting.
- Identification and tracking solutions (e.g. RFID) at PV components/modules/system level, to facilitate reverse logistics, sorting/inventory of PV and warehouse operations.
- Define and validate wide-range, standardised re-use PV module quality requirements with quantitative guidelines included for testing, sorting, repair

Re-used or repaired PV modules could serve as a source of spare parts for PV systems, prolonging those systems' operation.

System

» Demonstration Actions (TRL 5-7)

- Novel BOS components enabling multiple-re-installation of PV modules – adapted to multiple PV module sizes, weight, enabling fast and repeated installation without damage and durable for 50 years (e.g. in residential and urban context allow the PV system to be gradually adapted)
- PV module and system electronics, O&M adapted to deal with potentially disparate modules
- Study local solutions for local circular O&M strategies, supply chain for “spare” modules to enable 10-15+ years old PV system repair despite changing technologies

» Flagship Actions (TRL 7-8)

- Re-use PV operations are integrated in the EU O&M value chain
- (Automated) detection, diagnostics and classification (incl. recommendation) of repair or re-use operations in PV asset management tools for utility and commercial- and industrial-sized size PV plants
- Registering PV system decommissioning to gain insights in the addressable market volume
- Progressive revamping / repowering concepts to keep health status of PV plant high and ensure sustainability by developing reuse concept for obsolete (from an utility scale PV investment viewpoint) components

Value chain creation & New revenue streams

- Training of field actors (installers, certification bodies)
- Equipment development for repair and automated field testing dedicated to low-cost and high throughput operations
- Create acceptance, bankability from financial and insurance sector
- Define responsibilities, liability of original product provider and re-use operator, adequate product warranty implementation
- Explore novel business models related to re-use through service offerings
- Standardisation/TS for design qualification and type approval protocols, towards PV reuse-repurposing-recycling
- Synergies with innovators in supply chain / reverse logistics technologies, also leveraging e.g. AI/machine learning aided logistics, sorting, warehouse operations, inventory management for circular PV economy
- Recommendation about de-commissioning of PV plants (de-co plan mandatory)

The role of digitalisation:

- Comprehensive PV module data history will assist in sorting upon decommissioning PV plants, enabling adapted re-qualification tests for second life. Deployment of integrated PV module tracking technologies will facilitate the interaction between the different O&M service providers as well as the actors of the 2nd life, recycling. Last but not least, digital performance tracking could be a critical element to build trust towards second life PV modules from investors, insurers and owners.

Drone construction reporting. © Above Surveying

KPIs

KPI	Target Value (2030)
% repair/reuse after EoL of first life PV	>50 %
Years of operation for reused modules	>10 years
Cumulative lifetime minimum (defined as 80 % of initial performance)	40 years
Milestone	
Demonstrate increasing amount of repair/reuse up to 50-60 % and implementation of clear triage protocols in the EoL sector for first life PV < 15 years	

PV in Buildings. © Alius

Roadmap 3: Recycle and Recover

Rationale for support

Current PV modules on the market are not designed for circularity (meaning easy to disassemble, repair, refurbish, and recycle). They cannot be "re-opened" and the only way for recycling is through destructive processes such as shredding. The irreversible design severely limits repair/refurbish potentials, as well as the recovery of valuable materials.

There are multiple research initiatives in PV eco-design (such as CABRISS and EcoSolar). But despite the advancements in technological research, there is currently a clear lack of business incentives for manufacturers to implement design-for-circularity.

Following the material efficiency hierarchy, resources should be kept in productive use as long as possible and at the highest quality possible. Next to the development of reuse and repair strategies for photovoltaic system components, the license to operate for the PV value chain in the future will also rely on a strong circularity strategy when it comes to recovering materials and components from end-of-life photovoltaic systems. Given the longevity of these components and a continued exponential deployment trajectory towards multi-terawatt scale by mid of the century, design for recycling becomes a critical prerequisite for technology development. In particular for new module and cell concepts – such as multi-junction technologies, combining thin-film compound semiconductors, and perovskites with silicon – recycling strategies need to be developed and findings of these developments need to be shared upstream to improve design concepts. Product circularity information needs to be readily available to ensure the development of a low cost and widely accessible recycling infrastructure, embedded into existing WEEE recycling systems. To enable low-cost recycling, the inherent material value of secondary resources recovered from recycling needs to be valorised through a market pull for these materials. The development and definition of end-of-waste criteria for PV materials - be it scarce specialty materials, high-embodied energy materials, or bulk commodity materials - will play a crucial role in converting recovered waste fractions into marketable secondary raw materials for new PV production. Module design and material selection should encompass resiliency metrics, to ensure the acceptability of post-industrial and post-consumer recycled content.

From a holistic, life cycle environmental performance perspective, these measures will help to further improve the environmental footprint of PV electricity - and as such, the downstream environmental footprints of power-to-X conversions subsequently.

A majority of the lifecycle issues for PV systems can be improved through high value recycling:

Impact category	Root cause for process issue
Mineral, fossil and renewable resource depletion	Supply chain of semiconductor materials (cadmium, tellurium, indium), silver (mainly used in metallization paste for multi- and mono-crystalline Si PV modules), copper (mainly used in the electric installation) and zinc (used in various processes such as secondary aluminium production).
Human toxicity (cancer and non-cancer effects)	Cancer effects: disposal of redmud from bauxite digestion (supply chain of primary aluminium) and disposal of slag generated in the production of unalloyed electric steel – substance hotspots are chromium VI emitted to water and chromium emissions to air, both being primarily associated with the supply chain of steel production. Non-cancer effects: production of primary copper and zinc and related emissions from leaching residues and hard coal ash as well as zinc and mercury emitted to air in the process of unalloyed electric steel production and emissions of arsenic to water during the beneficiation of iron ore.
Freshwater ecotoxicity	Waste incineration of plastic components from the module and electric installation and the disposal of redmud from bauxite digestion (supply chain of primary aluminium).
Particulate matter potential	Supply chain of electricity, dominated by electricity production from Chinese hard coal power plants.
Acidification potential	Emissions of sulphur dioxide and nitrogen oxides to air due to operation of transoceanic freight ships, flat glass production and hard coal-based electricity production.

Measures that enable and encourage a circular economy and the decarbonization of the electricity mix would help to effectively relieve some major hotspots by addressing resource depletion of critical materials in module manufacturing, facilitating recycled content for primary materials in the BOS e.g. copper, steel, and aluminium, thereby reducing cumulative energy demand as well. [(59)]

Status

- End-of-Life recycling rate (EOL-RR) of Silicon (0 %), Indium (<1 %), Silver (~50 %, excluding jewellery) [[(60)]]
- No recycling of polymers
- No / limited high value recycling of glass - end-of-waste criteria fulfilled, however, insufficient for re-use as float cullet
- High value recycling of CdTe semiconductor material with 95 % re-use in new products established as best practice
- No/limited high value recycling of high purity silicon wafer or poly-silicon

Solar PV accounts for 10 % share in global silver consumption, 8 % for indium, and 5 % or less of the total production of MGS is used in the manufacturing of high-purity silicon for the solar and electronics industry.

(59) PV Quality and Economy (September 2018) https://etip-pv.eu/publications/etip-pv-publications/
(60) United Nations Environment Programme (2011). Metal stocks and recycling rates. https://wedocs.unep.org/20.500.11822/8702

Targets, Type of Activity and TRL

» Early-Stage Research Actions (TRL 2-3)

- Recycling value chain analysis of materials in the PV and global value chain of other end-user applications and prediction of PV share for these materials by 2030 and 2050.

» Development Research Actions (TRL 3-5)

- Dedicated chemical (and mechanical) recycling processes for extracted polymers from PV module waste (TRL4-5)
- Development of recycling processes for integrated PV with PV modules with variety of sizes, materials, etc. Creating clarity-link with construction element recycling sector.

» Demonstration Actions (TRL 5-7)

- Recovery of polymer fractions from PV module waste and further separation / sorting into the different material types

» Flagship Actions (TRL 7-8)

- Recycling of kerf: recovery of about 40 % of pure silicon, which is considered as waste when sawing a silicon ingot
- Use of post-industrial and post-consumer recycled PV glass in new PV glass manufacturing
- High value recovery of silicon from post-consumer end-of-life PV panels for material recovery in PV manufacturing / battery manufacturing / other silicon based industrial / material applications
- Specific criteria in WEEE regulation to boost the recycling of precious metals

The role of digitalisation

End-of-life of products is regulated by an extensive framework, including the Waste Framework, WEEE and Batteries Directives. An online platform that provides treatment, recycling facilities, and preparation for re-use operators with access to WEEE recycling information in line with the requirements of the WEEE Directive.

This could be welcomed by recyclers as a valuable source of information enabling efficient recycling of EEE, providing significant added value to the industry-supported collection schemes for end of life EEE. One example of such type of initiative is the Information for Recyclers Platform (I4R) [[61]].

KPIs

KPI	Target Value (2030)
Recycling of kerf	recovery of about 40 % of pure silicon
Recovery of polymers from PV module waste for chemical recycling	>90 % recovery of EVA, PVF, PVDF and PET
End-of-Life recycling rate (EOL-RR)	Silicon (90 %), Indium (30 %), Silver (70 %), Cadmium/Tellurium (95 %)

(61) https://i4r-platform.eu/

Roadmap 4: Technologies for sustainable manufacturing

Rationale for support

The need of accelerating the deployment of solar PV manufacturing projects in Europe is a critical milestone to strengthen the EU's leadership in Clean Energy Technologies and contribute to the re-industrialisation of Europe. An example of the needed initiatives is represented by the European Solar Initiative (ESI) which aims to scale up a strong PV manufacturing industry in Europe across the entire value chain from raw materials to recycling, which will capture the additional 20 GW of annual solar demand forecasted in Europe for the next decade. This will generate €40bn of GDP annually and create 400,000 new direct and indirect jobs across the PV value chain. [(62)]

To this as a main objective, the following items need to be considered:

- Low energy production processes or renewable energy use in production
- Circular fab approach: performance, quality, and sustainability:
- **Developing end-of-life strategies and processes**, such as refurbishment, remanufacturing or efficient recycling
- Study local solutions for local circular manufacturing & recycling adapted to the manufacturing site
- Use of recycled /waste materials in production
- Reducing manufacturing waste (water, chemicals, materials, gaz...)
- **Designing for longevity**, potentially with in-situ reconditioning
- **Selecting low-impact materials**, particularly secondary and biologically derived ones
- **Substituting primary & critical resources**, for earth abundant, renewable or recovered resources
- Quantify how degree of centralisation of manufacturing impacts sustainability (e.g. by supply chain length)

Status

The energy payback time for monocrystalline silicon-based PV systems is 0.8 to 1.3 years[41]. After this time, the panels have generated more energy than was required for their production. The impact of their production can also be measured by the volume of greenhouse gases (GHG) emitted that is not considered in the energy payback, which is between 17 and 40 grams of carbon dioxide per kilowatt hour of power produced by a typical monocrystalline silicon based PV system[41]. Designers and manufacturers should investigate ways of reducing both the energy and GHGs in production. [(63)]

Targets, Type of Activity and TRL

» Development Research Actions (TRL 3-5)

Target percentages for recycled and non-hazardous materials.

» Demonstration Actions (TRL 5-7)

Common strategies to achieve more circular designs include:

- Standardisation – both within a design organisation and between organisations
- Modularisation – to improve separability, reparability, and upgradability

Rethinking the design to improve the maintenance, repair, upgrade, refurbishment and/or manufacturing process.

Design for disassembly principles will provide guidance on how to design for a more efficient deconstruction phase and will be constantly evolving.

(62) https://europeansolarinitiative.eu/

(63) Sica, Malandrino, Supino, Testa and Lucchetti, 2018, Management of end-of-life photovoltaic panels as a step towards a circular economy

» Flagship Actions (TRL 7-8)

Legislated incentives to encourage manufacturers to close-the-loop on their supply chain. This could include a product stewardship scheme.

Labelling or materials passports that track and disclose material origin and composition, recyclability and repair process on panel. Global databases on panel contents.

Standardisation of panel design by industry and government to enable more efficient recycling, and to enable the waste industry to plan for future waste streams.

Roadmap 5: Eco-labelling and energy-labelling

Rationale for support

A life cycle assessment (LCA) is an important tool for evaluating the environmental profile of energy technologies, as the results can be used to guide life cycle engineering decisions of new processes and equipment. In this context, it is imperative to provide up to date, verified and widely accessible life cycle inventory (LCI) data for PV components in data bases (Ecoinvent, GABI, Life Cycle Data information system).

There is no doubt that data availability is key for setting standards based on accurate databases for material demand, flow, and impact throughout the life cycle. However, it usually takes about 4 to 5 years to update. Therefore, it is required to achieve a more dynamic database update, as PV technology evolves much faster than the LCI reference databases.

Need for accurate (and up-to-date) life cycle inventory databases is very clear and should indeed be a strong recommendation for future research projects - it should be evaluated, how the Eco-Invent Database, GABI database and the European Commission Life Cycle data information system could be updated through dedicated research - leveraging the results of the Product Environmental Footprint Pilot phase.

Status

- 3 to 4 years in IEA T12 to update (data availability is key)
- In the EU, the PV industry participated in the Product Environmental Footprint (PEF) Pilot Phase [(64)] and developed sectoral Product Environmental Footprint Category Rules (PEFCR) for Photovoltaic Modules used in photovoltaic power systems for electricity generation [(65)]. This validated the environmental performance of PV technologies in the EU, and better informed decisions on what EU sustainable product policies would be most appropriate for this category of products
- Latest JRC technical report with policy recommendations on ecodesign for modules and inverters, energy and ecolabel for residential systems and green public procurement (GPP) criteria for PV systems [(66)]
- Recommendations presented in the expert input paper – Eco-design & energy labelling for photovoltaic modules, inverters and systems in the EU [(67)].

Targets, Type of Activity and TRL

» Demonstration Actions (TRL 5-7)

- Holistic evaluation of sustainability performance with an Environmental Impact Index (EII), in which various influencing factors of industrial or other human activity to the environment are condensed in a way that the impact of such activity can be reconstructed and evaluated.
- Carry out an eco-design measure to promote reparability of photovoltaic inverters, and therefore to increase their lifespan. In this framework, the in-

(64) Product Environmental Footprint (PEF) Pilot Phase, https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

(65) PEFCR PV electricity v. 1.1; https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_v1.1.pdf

(66) Dodd, Nicholas; Espinosa, Nieves – JRC B5; Preparatory study for solar photovoltaic modules, inverters and systems, (Draft) Task 8 Report: Policy recommendations; December 2019

(67) Expert input paper – Eco-design & energy labelling for photovoltaic modules, inverters and systems in the EU. ETIP PV, SolarPower Europe, PVthin, European Solar Manufacturing Council, IECRE. 2021

verter should be constructed to allow access to and replacement of identified parts

» Flagship Actions (TRL 7-8)

- More dynamic database update
- Implementation of an EII. The proposed scale would be in alphabetical order from A through G, providing guidance with the following interpretation:
  - Levels A, B: Pass for GPP and ED/EL requirements
  - Levels C, D: Pass for ED/EL requirements, fail for GPP requirements
  - Level E: Fail for GPP, ED/EL requirements with minor deficiencies
  - Levels F, G: Fail for GPP, ED/EL requirements with medium / major deficiencies
- Implement requirements for GPP and Eco Label: EII minimum classification of "B" in every single category. As a transitional method, for some selected categories, a classification of "D" can be considered for an intermediate period of 2 years following the enactment of the directive.

KPIs

KPI	Target Value (2030)
Lifetime in Eco-design	40 years for PV modules (defined as 80 % of initial performance) 15 years minimum for all electronic / electro-mechanical components of the inverter, including the software needed for the full function of the device.
PV module Degradation rate in Eco-design	0.4 %/year
Delivery of the spare parts	Within 15 working days within Europe
EII classification	> 25 % Products (Modules & Inverters) with a minimum of "B"
Update of LCI database	Every year
Milestones	
Design for deconstruct strategies of tandem technologies, to separate top from bottom cells, and facilitate EoL management At least each individual printed circuit board and disconnectable component of the inverter must be provided as an independent spare part Annual update of the LCI database, including harmonization among the various reference publishers (IEA, ecoinvent, GABI ...)	

In the last decade and longer, photovoltaic module manufacturers have experienced a rapidly growing market along with a dramatic decrease in module price.

Such cost pressures have resulted in a drive to develop and implement new module designs, which either increase performance and/or lifetime of the modules or decrease the cost to produce them.

Objective 2: Reliable and Bankable Solar PV

The reliability and lifetime of a PV plant depends mainly on the quality of the components.

Various international activities are actively studying how to increase performance and reliability of PV modules and systems, e.g. the IEA PVPS Task 13 [(68)], the COST Action PEARL-PV [(69)] or the H2020 project Solar Bankability [(70)] which provided the basis for the establishment of a common practice for professional risk assessments. The most effective strategy for reliable and bankable solar PV is to prevent the occurrence of failures and by reducing the impact of failures once they become evident. In new PV projects, the focus must be on the application of novel preventive mitigation measures to minimise the probability of failure occurring once the PV plant is in operation. For existing PV projects, advanced data driven mitigation measures need to be developed to go beyond the state-of-the-art concept of corrective maintenance as well as progressive repowering interventions to extend plant lifetime and increase the production capacity without requesting additional space. All data coming from the various phases carry important information that can only be fully exploited by the community as a whole if the data can be stored and transferred along the value chain. The ultimate goal is to be able to "quantify" quality in a "value chain" approach by not being locked in a specific phase so that a PV project in the future can have access to lower WACCs by presenting bankable approaches, products and services.

PV projects in any market segment require a dedicated technical risk framework where the requirements may vary depending on the complexity of the project. In general terms, initial risks need to be identified and quantified and all the stakeholders operating in various phases along the value chain need to be involved to vastly reduce and minimise the residual risks. This can be done by **preventing the occurrence of failures and by reducing the impact of failures once they become evident**. Technical risks which cannot be transferred to other stakeholders will ultimately stay in the hands of the PV project owner. A clear technical risk framework is important as it can "quantify" the quality of a PV project and thus demonstrate the advantages in terms of business model (more reliable generation for a longer lifetime) compared to other projects of lower quality. A project perceived of high quality by lenders (in terms of equity or debt) will have access to lower WACC (Weighted Average Cost of Capital) which is the most important parameter affecting the LCOE [(71)] (Levelised Cost of Electricity), and ultimately the IRR (or other benchmarks). Quality in PV projects starts from the planning phase where a fundamental role is played by the accu-

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(68) https://iea-pvps.org/research-tasks/performance-operation-and-reliability-of-photovoltaic-systems/

(69) https://www.pearlpv-cost.eu/

(70) http://www.solarbankability.org/home.html

(71) Vartiainen, E, Masson, G, Breyer, C, Moser, D, Román Medina, E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Prog Photovolt Res Appl*. 2020; 28: 439– 453. https://doi.org/10.1002/pip.3189

PV in Buildings. © Zigzag

racy and uncertainties related with the yield assessments. **A yield assessment with reduced uncertainties** (thanks to improved models and access to better site dependent data, e.g. irradiance) **can lead to a much more favourable business model.** Procurement is the next important step where **extended testing beyond what is prescribed by the standards can increase the confidence of the right choice of PV components.**

It is during these two steps that the remuneration of PV projects can be vastly improved by ensuring a reduction in failure rates and a more positive business case. After a successful implementation of these preventive mitigation measures, the PV project needs to focus on the transportation and installation phase where quality assurance needs to be included to make sure that all the components are in their best conditions for the operational phase. A reliable generation for a longer lifetime can then be ensured by **innovative O&M practices which include data-driven measures coming from both field experience and monitoring.** Finally, all the information collected along the whole value chain need to stream into **digital platforms that can act as a decision support system for the best actions to follow in case of deviations.**

Roadmap 6: Quality assurance to increase lifetime and reliability

Rationale for support

In the last decade and longer, photovoltaic module manufacturers have experienced a rapidly growing market along with a dramatic decrease in module prices [72]. Such cost pressures have resulted in a drive to develop and implement new module designs, which either increase performance and/or lifetime of the modules or decrease the cost to produce them. Many of these innovations include the use of new and novel materials in place of more conventional materials or designs [73]. As a result, modules are being produced and sold without a long-term understanding about the performance and reliability of these new materials. This presents a technology risk for the industry. In the past, several unexpected degradation mechanisms appeared after a few years of operational time in the field although they were not detected in any laboratory accelerated testing. Examples range from Potential Induced Degradation (PID) [74], Light and elevated Temperature Induced

(72) A. Jaeger-Waldau, "PV Status Report 2019," Publications Office of the European Union, Luxembourg, 2019. Accessed: Jan. 17 2020. [Online]. Available: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/pv-status-report-2019

(73) VDMA, Ed., "International Technology Roadmap for Photovoltaic (ITRPV): Results 2018 inclduing maturity report 2019," Oct. 2019. Accessed: Jul. 23 2020. [Online]. Available: https://itrpv.vdma.org/

(74) S. Pingel et al., "Potential Induced Degradation of solar cells and panels," in 2010 35th IEEE Photovoltaic Specialists Conference,

Degradation (LeTID)[(75)] or back sheet cracking[(76)] appeared after a few years operational time in the field although they were not detected in any laboratory accelerated testing.

Consumers and manufacturers rely on international standards, such as those from Technical Committee “Solar Photovoltaic Energy Systems” TC 82, or testing procedures proposed by international initiatives such as PVQAT[(77)] or test institutes to ensure that PV modules do not result in unexpected performance or reliability problems. However, testing procedures and also standards often have to be adapted to suit new module technologies or reflect new degradation modes. Another issue is that module manufacturers do not typically advertise their bill of materials (BOM) and the BOM for a particular module model can vary depending on when and where it was made.

Status

A “one module type fits all” approach is still widely used in the PV industry, where one standard module design and unified material quality level composition is used for applications in widely varying environmental and climatic conditions and setups around the world. Due to the high cost pressure, new materials, components or module designs that promise a reduction of LCOE are brought into the market at a very early stage. Examples for recent changes are new wafer and module sizes, replacement of Al-BSF cells with PERC and SHJ cells, half cells, new interconnection technologies (multiwire, shingling), new polyolefin encapsulants and back sheets and so on.

Currently the industry relies mostly on extended IEC testing for qualification of new module designs. However, these are single stress tests that do not replicate typical operating conditions of PV modules. Hence, the aforementioned field failures were not detected during module qualification testing. Recently a lot of effort has been put into development in sequential or combined test approaches, such as MAST[(78)] or CAST[(79)] tests. However, these approaches are elaborate, time consuming and expensive, and therefore are mostly used for R&D purposes, but not widely used for module qualification in the PV industry.

Targets, Type of Activity and TRL

PV Module development

» Development Research Actions (TRL 3-5)

- Innovations to reduce module environment temperature in hot and dry climates in order to increase energy yield

» Demonstration Actions (TRL 5-7)

- Database/Design Tool for material and component selection with respect to climatic or environmental conditions of PV system

» Flagship Actions (TRL 7-8)

- Virtual prototyping tools to predict thermo-mechanical failure probability in the design phase

Honolulu, HI, USA, Jun. 2010- Jun. 2010, pp. 2817–2822.

(75) M. A. Jensen, A. E. Morishige, J. Hofstetter, D. B. Needleman, and T. Buonassisi, “Evo-lution of LeTID Defects in p-Type Multicrystalline Silicon during Degradation and Regen-eration,” IEEE J. Photovoltaics, vol. 7, no. 4, pp. 980–987, 2017, doi: 10.1109/JPHOTOV.2017.2695496.

(76) G. C. Eder et al., “Error analysis of aged modules with cracked polyamide backsheets,” Solar Energy Materials and Solar Cells, vol. 203, p. 110194, 2019, doi: 10.1016/j.solmat.2019.110194.

(77) The International PV Quality Assurance Task Force. https://www.pvqat.org/

(78) W. Gambogi et al., “Development of Accelerated Test Sequences to Assess Long Term Durability of PV Modules,” 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), Chicago, IL, USA, 2019, pp. 2406-2410, doi: 10.1109/PVSC40753.2019.8981222.

(79) Owen-Bellini, M, Hacke, P, Miller, DC, et al. Advancing reliability assessments of photovoltaic modules and materials using combined-accelerated stress testing. Prog Photovolt Res Appl. 2021; 29: 64– 82. https://doi.org/10.1002/pip.3342

PV Module qualification

» Flagship Actions (TRL 7-8)

- Combined stress test infrastructure for qualification of new PV module designs
  - Climate-specific (e.g. for use in deserts or tropical regions)
  - Application-specific (e.g. floating PV, BIPV, AgriPV, etc.)
- Established methods for module forensics

Lifetime and yield prediction

» Development Research Actions (TRL 3-5)

- Development of data-driven and/or physical models for prediction of (remaining) lifetime of PV modules and PV systems based on accelerated life cycle testing
- Development of a methodology to determine the long term degradation and performance loss rates from several years of operation data.

» Demonstration Actions (TRL 5-7)

- More accurate yield assessments and LTYP. Novel technologies and system design require more accurate models for the determination of Yield Assessment and Long-term Yield Prediction

The role of digitalisation

Comprehensive generation of relevant data during production and operation of photovoltaics will be a key feature for enabling enhanced quality assurance of PV. This includes automated data processing (e.g. feature selection, image analysis and data reduction), statistical modelling to find correlations and the creation of predictive models (data driven or physical) describing long term behaviour of photovoltaic modules and systems.

KPIs

KPI	Target Value (2030)
Proven lifetime of PV modules through extended testing (defined as 80 % of initial performance)	40 years
Accuracy of yield assessments for new technologies and novel system design with uncertainty (1 sigma)	<5 %
Milestone	
Establishment of European testing capacities for combined or sequential stress tests	

Roadmap 7: Increased field performance and reliability

Rationale for support

From multi-MW utility scale down to small systems on residential roofs, electricity generated by photovoltaic systems is changing the energy landscape as we know it. GWs of capacity are added worldwide year after year where the cumulative 1 TW goal could be achieved already in 2022. By the end of the next decade the TW annual market could become reality. PV already represents a share of more than 8 % of the electricity generation in some countries (Italy, Germany, Greece, to name a few) and with these values in mind the penetration levels will quickly reach the double-digit all-over Europe. It is within this scenario that the PV sector must ensure that the installed power capacity in GW can also reliably generate TWh of electricity for an extended lifetime.

The introduction of novel technologies and novel PV system design makes the need of increased field performance and reliability a continuous industry demand. Solutions and services which are already available in the market or close to the market will need to be continuously updated and redefined to capture innovation trends. Moreover, new technologies can introduce new degradation modes once in the field.

Status

Field PV diagnostics, mainly in the form of infrared (IR) and electroluminescence (EL) imaging – and recently the emerging ultraviolet fluorescence (UVF) imaging – are PV O&M tools typically auxiliary to string/inverter level PV monitoring. Often combined with analysis of electrical signatures, these inspection methods can identify, with high spatial resolution, the (potential) presence or evolution of different failure modes of PV modules and their exact physical location in a PV plant. At earlier research/pilot level, several research groups have implemented and demonstrated experimental setups for aerial-IR and daylight EL imaging inspections and fault diagnosis in MW-scale PV plants, employing drones or unmanned aerial vehicles (UAVs). Typical IR inspection rates reach up to 4 MW (of PV system size) per hour, corresponding to net flight time, though complete studies (i.e. inspection, manual data treatment, diagnostic analysis, reporting) require 6-8 times longer time for the same system size. More recently, broad adoption of EL- and (mostly) IR-based PV diagnostics has been accelerated through technical standardization, technology collaboration platforms and recent technological advances in drone-based imaging and digital mapping. ***As such, today, aerial-IR imaging attracts high attention, emerging among the best practices for PV O&M and as the cornerstone for advanced, large-scale failure diagnostics for PV plants. Turnkey aerial-IR inspection services are offered, including artificial intelligence (AI)-based data analytics, fault diagnostics and reporting as well as consulting, i.e. recommendations for corrective maintenance actions to PV asset owners and O&M engineers***

The detection of failures in the field and the subsequent action are triggered by:

- Periodic field inspection which are contractual obligations for O&M operators
- Alarms generated by monitoring systems

State-of-the-art commercial solutions for PV monitoring, allow for monitoring the operational state of PV systems and pinpointing performance issues in real-time and high temporal granularity, from system up to string/array or inverter level. In principle, as defined in the IEC 61724, such solutions involve: i) monitoring hardware for on-site logging of acquired electrical outputs (inverters, strings, meters) and weather data (e.g. irradiance, ambient temperature), coupled with ii) management software for remote performance management, data visualisation, KPI calculations, reporting, alarming and ticketing. The most advanced PV yield monitoring and fault diagnostic tools offer software-driven quantification and classification of string/inverter-level failures, as well as data analytics for soiling rates and performance degradation. On the other hand, other platforms offer supervisory control and data acquisition (SCADA) features, tailored for utility-scale PV plants. Yet, particularly for utility-scale PV systems monitoring and diagnostic needs are significantly complex and demanding. As of today, detection and assessment of underperformance in PV plants are typically executed in a semi-manual top-down approach, analysing low performing components (e.g. PV modules) by drilling down from substations, inverters to strings and junction boxes.

On this basis, monitoring-based fault analysis and diagnosis are time-consuming, expert dependent and often of insufficient spatial granularity. As a result, several underperformance issues and failure modules – especially on PV module level – may either remain undetected, trigger "false alarms" or their root-cause stays unidentified.

Targets, Type of Activity and TRL

The introduction of novel technologies and novel PV system design makes the need of increased field performance and reliability a continuous industry demand. Solutions and services which are already available in the market or close to the market will need to be continuously updated and redefined to capture innovation trends. Moreover, new technologies can introduce new degradation modes once in the field.

» Development Research Actions (TRL 3-5)

- Development of algorithm for predictive maintenance to avoid component failures
- Embedded sensors and use of on-site autonomous UAV to enable continuous and cost-effective field diagnostics for optimal O&M strategy and analysis of failure evolution

» Demonstration Actions (TRL 5-7)

- The conceptualisation, innovation and deployment of EPC and O&M friendly PV components and system designs
- Hybrid or integrated monitoring-diagnostic imagery solutions for maximum spatiotemporal granularity and diagnostic resolution. Multispectral imagery inspections linked with electrical signature; synchronisation of field techniques with monitoring
- Diagnostic and field inspection enabled by novel features in PV components (fully automated diagnostic techniques)
- Early alert detection system for Potential Induced Degradation (PID)
- Effective and large scale use of metrics (e.g. CPN) to optimise O&M strategies
- "Complete" diagnostics, e.g. by IR inspections → fault detection, identification and loss analysis up to module/submodule level → minimize or even eliminate any dependence of IV tracing (time-consuming, costly, yet still required and applied today)
- Interoperability, standardization and auto-configuration of sensors, data acquisition, inverters and communication systems within PV plants and between PV plants and central monitoring systems (Industry 4.0/internet of Things)
- Smart control/tracking systems (e.g. coupled with real-time monitoring data, e-yield forecasting, EMS, meteo, etc) for performance optimisation in specific PV applications (e.g. optimised self-consumption in micro-grids; optimised energy/crop production in agri-PV; "self-protection" under extreme events in harsh environments, e.g. dust/snow storms).

» Flagship Action (TRL 7-8)

- Development of data-driven and/or physical models / Reliability models of PV modules, inverters and other BOS components to predict the lifetime based on field data including climate dependent stress factors
- Creation of a large-scale database of PV plant performance to increase the knowledge in terms of performance ratio, performance loss rates, climate and other stress factors dependency to be used for the development of algorithms, models, etc +
- Interoperability of databases at EU member state level for incentivised PV systems (Mandate through RED directive to share performance of incentivised PV systems as open data in compliance with GDPR)

The role of digitalisation:

Digitalisation will enable the creation of BIM/Digital Twin concepts which will allow an asset to be properly followed along the whole value chain down to component level. From the manufacturing phase, through EPC, O&M and end of life

KPIs

KPI	Target Value (2030)
Inspected PV plants using (semi)-automatic EL/PL	20 MW/day
Inspected and analysed PV plants using aerial IR (referring to low-altitude IEC compliant detailed IR inspection)	6 MW/h
Failures or underperformance issues identified (root-cause analysed) and recovered or isolated;	>90 %
Cost Priority Number of PV system (total cost of O&M, insurance, warranty, etc.)	<10 Euro/kWP/year
Diagnostic accuracy for automated aerial IR imagery: false negatives/positives	<10 %
Diagnostic accuracy: modelled / calculated power loss for automated IR imagery	>95 %
On PV plant level, common annual performance ratio (PR) including periods of unavailability and after correction for expected degradation in the field.	85 % for residential and small commercial plants and 90 % for other plants
Proven system energy output per year; (verified by extrapolating performance loss rate analysis and defining contribution at single component level,)	at least 80 % of initial level for 40 years by 2030 PV module degradation 0.4 %/y
Cost reduction on today's per-schedule preventive or corrective O&M as a result of reducing failures and limiting unnecessary O&M tasks and predictive maintenance	by 10-15 %
Size of large-scale PV performance database	50 GW included in the database with at least 3 years of average operational time by 2025 and 100 GW with at least 7 years of average operational time by 2030

Warranty and contractual terms are not well standardized in the PV industry. There is no total transparency on how the manufacturers and contractors define internally their risks corresponding to their specific warranties and contractual terms.

Roadmap 8: Bankability, warranty and contractual terms

Rationale for support

For most PV plant development projects operated by Company X, 65 – 75 % of the investment is provided through debt financing from various lenders. Utility-scale PV plants are investments in the thousand- to several million € scale. The following items are needed to reduce risk and increase bankability:

- Improve EPC and O&M contracts
- Improve accuracy of design and construction monitoring
- Improve data-driven O&M
- Increase PR%, confidence in the estimated production and costs during the operations phase
- Give practical recommendations to ensure that the PV bankability meaning identified and quantified risks can be applied by all decision makers

The interest rate on the aforementioned debt can be typically reduced by 1 percentage point if a risk framework is in place thus increasing the Internal Rate of Return (IRR) by up to 2 percentage points.

PV Bankability has been subject of specific analysis by H2020 SolarBankability project in 2015-2017 (www.solar-bankability.eu). The aim of this revisiting is establishing the recommendations regarding the warranty and contractual terms at three levels of risk: low, medium and high risk. The main equipment to be considered are PV modules, inverters and mounting structures and the contractual schemes will be EPC contract and O&M contract.

The main challenge is to predict the impact of new technology developments entering the markets that will be dominant in the medium term. The players of the industry should have a road map of how the new technology developments will impact the recommendations considered here.

Status

- Non optimised EPC contracts (depending on which stakeholders, KPIs definition for hand-over phase to be improved)
- Non optimised O&M strategies which leads to non-optimised O&M contracts (schedule maintenance is contractually determined and not based on hard facts)
- The current warranty terms of PV modules, inverters, supporting structures, EPC contract and O&M contract are not typically connected to the quality of the equipment and service offered. The gap is a risk that should be identified and quantified.
- Warranty and contractual terms are not well standardized in the PV industry. There is no total transparency on how the manufacturers and contractors define internally their risks corresponding to their specific warranties and contractual terms. Therefore, it is quite impossible for developers and investors to quantify the risk assumed in each individual project because the benchmarking is not possible with the mentioned lack of transparency.
- There is not an agreed Risk framework for PV plants as a de risking strategy

Targets, Type of Activity and TRL

» Development Research Actions (TRL 3-5):

- Product warranties should be based on hard facts derived from statistical analysis and not on unrealistic requirements (i.e. cover infant failures, however include cost of longer warranties in the cash flow models). Moreover, the insurance companies/developer/investors/lenders should have the elements from the information shared in the warranty terms to identify the associated risk and insurance cost.

» Demonstration Actions (TRL 5-7):

- O&M contracts based on new strategies (optimised predictive and corrective maintenance and optimised periodic maintenance)

- EPC contracts giving the option of several warranty levels with different associated costs. The risk assumed will be quantified and benchmarking of different projects will be possible.

» Flagship Action (TRL 7-8):

- Develop progressive repowering schemes to cost-optimise investments, assets, encourage re-use of components, use of land. Develop dynamic lifetime yield prediction tools to include revamping and repowering (TRL7)

- Develop a de risking framework to achieve low WACC for PV as low risk investment (TRL7)

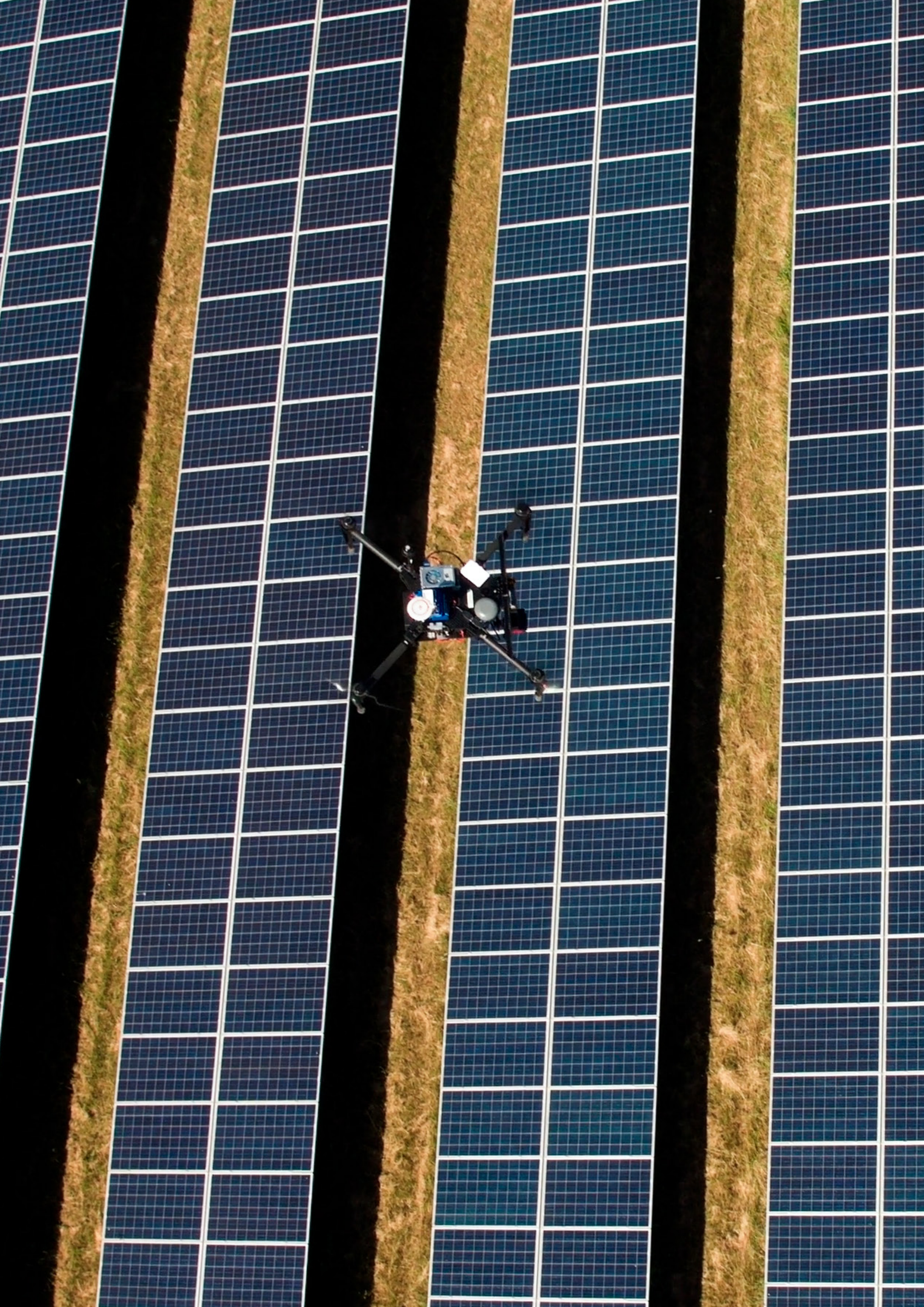
The role of digitalisation

Digitalisation will allow the sector to follow the history in terms of reliability and quality assurance (see roadmap 6 and 7) at component level. Choices made at a certain stage of the value chain will be recorded in digital platforms. Economic impact of these choices will be quantified. All of these will enable the creation of tailored made risk assessments.

KPIs

KPI	Target Value (2030)
Typical WACC of utility scale PV	Reduced by 1 % compared to base level
O&M costs	Reduced by 33 % thanks to optimisation in contracts
Milestone	
Define standardized contractual KPIs for EPC Define the warranty levels of modules, inverters and supporting structures with associated risks	

Drone surveying panels. © Above Surveying →



CHALLENGE 3

New Applications through Integration of Photovoltaics (for Diversified and Dual-Purpose Deployment and Enhanced Value)

PV-enabled products must meet the requirements and standards of the original product or environment. Rules and regulations must be harmonized more closely across the EU to create markets large enough to address cost-efficiently. As most of 'IPV' supply and value chains are based in Europe, the integration of PV creates huge opportunities for European value and job creation.

Objective 1: Physical integration of PV into the built environment, vehicles, landscapes and infrastructures

The inherent modularity of the PV enables it to be installed in systems from Watts to Gigawatts. This allows it to be integrated seamlessly into many different objects and surroundings, allowing space to be used efficiently:

- BIPV (Building integrated PV)
- VIPV (Vehicle integrated PV)
- Agrivoltaics and landscape integrated PV
- Floating PV
- IIPV (Infrastructure integrated PV)
- Low-power energy harvesting PV

It will soon become a priority in cities put PV on every roof and façade, starting with those with the best orientation.

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← PV in Buildings. © Wellsun

Roadmap 1: PV in buildings

Rationale for support

It will be essential to decarbonize the energy used to run and construct buildings. 'Nearly zero energy buildings (nZEB) are being promoted by national and international regulations, and require the integration of renewable energy systems. A closer coordination with the EU's Bauhaus initiative would be beneficial. Decarbonisation is driving electrification, for example through the use of heat pumps for heating and cooling, as well as increasing need for charging of electric vehicles (EVs). PV is expected to play a crucial role as the most important technology for the supply of electrical energy of buildings. Buildings offer the possibility of consuming PV electricity close to its place of production (creating savings in grid investment) and of generating PV electricity without taking up more land. PV in residential and commercial buildings are expected to make up half of PV installations globally until 2050.

Status

The "PV in buildings" sector is hampered by an absence of scalable solutions, but also at the regulation level, which lacks harmonization between PV and building sectors regulations and between unclarified sharing of area between PV, windows and 'green façade' elements. On the other hand, in the past decade, technology for aesthetic and functional integration of solar PV into buildings has been developed. Recently, the research focus has moved towards integrating PV with building systems using building information modelling (BIM), aided by progress in techniques to acquire and process data.

Targets, Type of activity and TRL

» Action I: PV module and BOS technology development (TRL 4 to 8)

Action I focuses on technology development at PV module and BOS level, considering both opaque and transparent envelope parts (e.g. solar windows, smart and bi-facial solutions).

Important research topics are: yield-friendly colouring techniques (including hidden PV), structural flexibility, module flexibility, suited voltage levels, the use of and combination with (building) materials other than glass, new encapsulation technologies, and an overall high aesthetical value that addresses the requirements of architects and designers.

Other important research topics are: resilience against partial shading, the interconnection of PV modules that have different sizes, specific thermal control solutions, service life/easy replacement, security of maintenance, software control for quick detection of faults, module substructures and fixing systems to enhance at the same time PV system aesthetics and electricity yield.

In order to decrease costs and enhance quality, reliability and sustainability new approaches are needed both for PV module and BOS development for industrialized mass-production of customized products and development of prefabricated BIPV façade and roof solutions, that incorporate an integrated life cycle approach.

These technology developments require PV/BOS manufacturers, universities, research centres, architects and designers to work together in (we suggest) "prototyping hubs".

» Action II: PV in buildings business models, value proposition, design and energy integration (TRL 5 to 8)

- Form alliances between all stakeholders (both from PV and building sectors, namely investors, owners, architects, installers) with the goal of developing new "solar-activated" building elements.

- Develop new schemes and business models for overall responsibility and concepts in order to activate BIPV as game changer for the re-financing of renovations (more favourable legal and economic boundary conditions for energy communities are needed for large-scale implementation).

- Develop energy integration concepts and social behaviour to maximize the energy matching between PV production and local buildings consumption, supported by new tools and business models to ensure their economic effectiveness)

» Action III: PV in building regulations (TRL 8-9)

Adapt standard EN 50583:2016 – *Photovoltaics in buildings* (which applies to modules) for BIPV elements by designing appropriate new tests.

- Create a new European standard, accepted across the EU looking at the safety of construction and PV, but the interaction between the two can give completely different results;

Buildings offer the possibility of consuming PV electricity close to its place of production (creating savings in grid investment) and of generating PV electricity without taking up more land.

- Territory level, i.e. from local to regional to national to EU level. Fragmentation of territory regulations leads also to conflicting requirements (e.g. local/national application rules for building permits, individual/local/national application requirements professional certification schemes for BIPV installers, national safety regulations for implementation of innovative BIPV solutions)

KPIs

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
PV in Buildings Systems Recyclability	By 2025: "PV in buildings" systems recyclability improved by 20 % when compared to 2020 levels; Improvement of operation and maintenance towards operating lifetimes of all technologies > 35 years By 2030: recyclability improved by 50 % when compared to 2020 levels
Cost of Manufacturing	By 2025: Reduced cost of manufacturing, installation and operation of "PV in building" technologies by 20 % compared to 2020 By 2030: reduced cost of manufacturing, installation and operation of "PV in building" technologies by 30 % compared to 2020
Building and District Energy Matching indicators	By 2025: Building and district Energy Matching indicators improvement through optimal "PV in buildings" system design: annual building electricity demand coverage > 40 %, building electricity self-sufficiency > 20 %, building electricity self-consumption > 70 %. By 2030: Building and district Energy Matching indicators improvement through optimal "PV in buildings" system design: annual building electricity demand coverage > 50 %, building electricity self-sufficiency > 30 %, building electricity self-consumption > 80 %.
BIPV Cost-Effective Solutions	By 2027: development of BIPV cost-effective solutions supported by advanced economic and business models for investors with PBT < 10 years.

Roadmap 2: Vehicle Integrated PV

Rationale for support

Electrification of the transport sector by massive deployment of E-mobility, while relying on renewable energy only, is an important step towards an environmentally friendly and sustainable energy system. Vehicle integrated photovoltaics (VIPV) provides the most intuitive solution by converting solar energy directly on the vehicle. In addition, it utilises extra and usually unused areas for solar energy generation and it hence stands for a true added value to the vehicle.

In a nutshell, the main challenge that exists today related to VIPV solutions is the fact that there is a lack of profound proof of environmental and economic benefits of VIPV. This is related, on the one hand, to the fact that this is a quite new application for widespread PV and, on the other hand, to the huge variety of use cases. The PV can be installed on/integrated in a variety of vehicles (trucks, caravans, passenger cars etc.), can be used for a variety of use cases (range extension, auxiliary, refrigeration etc.), and can be based on a variety of PV technologies (silicon based, III-V based, organic based etc.). Hence, the following items should be tackled.

- Standardization of data collection
- Establishment of shared database
- Specification of VIPV benefit
- Homologation of PV components
- Recycling of VIPV components
- Cost-competitive manufacturing
- Long-term sustainability

Status

Even though VIPV was already introduced in the 80s, it is just recently with the drastic decline of the PV system cost, and strong increase of the popularity of electric vehicles (EV), that VIPV is brought more and more into the spotlight. Still, only few EV models with VIPV are currently available, mostly as prototypes. Many solutions exist for VAPV (vehicle-applied photovoltaics), where PV modules are mounted on existing vehicle surfaces after the vehicle have been completed, especially for commercial vehicles, buses and caravans. EV startups from EU and USA are promoting VIPV for passenger car market, mostly in EV prototype stage and partly with series production announced. Two automotive OEMs from Japan and Korea are active with series production, while large car companies in EU are still with R&D efforts and prototypes. Glass manufacturers' interest in VIPV has been aroused. Several glass manufacturers worldwide have presented planning or prototype PV glass roof. VIPV passenger car boom is yet to come, while expectation for it is growing.

Targets, Type of activity and TRL

Demonstration at least at pilot line level of manufacturing for cost competitive VIPV products as well as the demonstration of their affordability, sustainability, modularity, and synergies will be necessary. Different cell, interconnection and encapsulation technologies and materials need to be tested, evaluated, optimised, and categorized for different VIPV use cases and different types of vehicles. It will be mandatory to address European PV value chain to support VIPV manufacturing as well as to expand the European PV value chain deeply into automotive sectors by involving and encouraging stakeholders. A TRL of 6-8 is expected. System level activities to address environmental, economic, and societal impact of VIPV as well as to clarify safety, recyclability, and grid compatibility issues will be important to strengthen the bankability of VIPV and the confidence of policy makers to put supportive regulatory measures. Development of the methodology for comparison of different technologies on different vehicle types is mandatory, since this will give investors, OEMs, etc. the ability to understand the specifications required for VIPV.

KPIs

Rapidly changing shadowing of the PV during driving impacts the PV module development for VIPV, as partial shading patterns require specific interconnection layouts and ultra-fast maximum-power-point tracking. Furthermore, cleaning and (partial) repairing of the PV modules should be possible in case of small impacts, scratches or damages. Other legal technological requirements surpassing the PV standards result from recycling and safety demands for automotive industry. An intelligent technology needs to be developed to connect the VIPV system with the grid or buildings (V2G, V2B) to balance sources and drains of the grid at any time during parking, while still charging the EV battery. Furthermore, aesthetical requirements (desired colors, homogeneity) must be fulfilled to significantly increase the social acceptance of VIPV.

PM Efficiency- SolarOnTop- Vos Logistics.

Solar on top.

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Data Collection	Development of a shared database and standard of data collection for mobile PV applications including the specification and the definition of environmental and economic benefits of different use-cases, regions, and vehicle types. (2025)
Technological Advancements	Definition of specific technological requirements for PV application in EVs with respect to safety, electro-magnetic compatibility, recyclability, etc. aligned with EU road and vehicle requirements and safety standards. (2027)
Manufacturing	Demonstration at pilot line level of manufacturing for cost competitive VIPV products and their long-term sustainability (2030)

"Agrivoltaics" is the simultaneous use of land for agricultural and photovoltaic usage but policies to promote it are lacking.

Roadmap 3: Agrivoltaics and landscape integration

Status

"Agrivoltaics" refers to the simultaneous use of land for agricultural and photovoltaic usage. In short, crops and electric power can be harvested on the same plot of land. Agrivoltaic systems can be roughly classified based on their module orientation: chiefly "horizontal" systems with high ground clearance and chiefly vertical systems. Both types might include bifacial modules, but bifocality is necessary in the vertical variants. Partially transparent modules are also highly relevant here to mitigate crop loss effects due to shading. Agrivoltaic systems can be realised with both fixed or solar tracking capabilities. Such tracking systems offer more flexibility in the light management for both agriculture and power generation, displaying a dual-yield control synergy unique to the agrivoltaic context. In comparison to other markets, European progress is significantly slower with relationship to its expansion potential. One reason could be the lack of concrete EU policy standards. Some potential to alleviate these issues could be found in the renewal of the Common Agriculture Policy (CAP), whereby the goal is set to reduce greenhouse gas emissions in the agricultural sector by 40 % until 2030. The use of agrivoltaics could strongly support these goals, but exclusion of land with agrivoltaics from CAP subsidies, may render the business case more difficult.

Targets, Type of activity and TRL

Dependent on the targeted agricultural context, agrivoltaics installations find themselves between TRL 3 and 8. To push this range more toward the higher end of the TRL range, there is a workstream focusing on the goal of defining legal rights issues for agrivoltaics in Europe. However, France has set a good example regarding rights issues. Along with Japan and USA (Massachusetts), France has introduced one of the few agrivoltaics targeting policies enacting an innovative tender scheme in 2017. In Germany agrivoltaics will be part of the innovation tenders though it is not yet sure what that concretely means for innovation. To ease this situation in Germany, an industrial and research consortium developed a pre-norm for agrivoltaics that should ease the way towards a reasonable international and/or European policy framework regarding agrivoltaics. Despite not having a clearly defined legal framework for construction, agrivoltaics is being followed by many different closely collaborating research institutes, operating with each other to conceive and plan projects. Semi-transparent and bifacial module types show great promise in tuning the light conditions for plant needs and have become a key focus in these projects due to their stronger economic case in such a mixed context. The strong independent networking of research, industry, and associations would also suggest the will to establish national or international networks. Moreover, the economic attention for agrivoltaics and the number of installed agrivoltaic systems are increasing yearly.

Despite existing agrivoltaic systems showing promising results and the industry showing more and more interest in the technology, many regions lack policies to expand agrivoltaics. Detailed life cycle analyses will be a critical point in understanding the future of agrivoltaics. Using the existing systems installed so far in Europe, one should not miss the chance to implement a second generation of agrivoltaics adapted in different ways to many regions and plant species in the world not only to gather new information, but also to make a big step in reducing our greenhouse gas emissions. The main vision for a Europe-wide agrivoltaic research roadmap is to identify the most synergetic plant-photovoltaic techno-agricultural layouts by 2025, for further evaluation by 2027 and implementation in utility-scale power plants by 2030, with the forementioned dual yield quantifications as KPIs in guiding this process.

↑ Research project to evaluate the synergies between apple cultivation and agrivoltaics in Rhineland-Palatinate, Germany. © Fraunhofer ISE.

KPIs

With the growth of agrivoltaic construction projects, it's becoming increasingly important to ensure the presence of positive synergies in installations and also to research larger, industrial scales comparing the systems to reference plots close by to evaluate the plant yield. The evaluation of these synergies naturally leads to two general key performance indicators resultant from the combined agricultural and photovoltaic system: plant yield and photovoltaic yield. A standardized methodology to evaluate this dual purpose would be beneficial.

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Plant Yield (economic value not only defined by weight, but also by quality)	Study and identify the most applicable use cases (crops) based on climate and local agricultural necessities (2027) Integrate rainwater collection by agrivoltaic installations in optimised watering strategies (2030)
Photovoltaic Yield (impacted factors such as varying network feed-in tariffs and self-consumption)	Understand visual impacts of agrivoltaic installations and how to influence public acceptance (2025)

Europe has 20,000 square kilometres of manmade reservoirs, on which 200 GW_p of PV could be economically installed if 10 % of that surface were used.

Roadmap 4: Floating PV

Rationale for support

Europe has 20,000 square kilometres of manmade reservoirs, on which 200 GW_p of PV could be economically installed if 10 % of that surface were used. In addition to this, offshore PV could be explored in sheltered and even in exposed locations.

The main market driver for floating solar is the search for area in locations with a high population density. Other advantages are: the cooling effect from the water, easy tracking by rotation of a whole platform instead of individual or small numbers of modules, reduced evaporation, reduced algae growth, easy and fast installation. Floating solar on dams for hydropower or in conjunction with wind energy induce synergies on the integration into the energy system

Status

Floating solar (FPV) is in rapid development, with globally close to 2GW_p of installed capacity. Approximately 400 MW_P has been installed in Europe, of which 100 MW_p in The Netherlands alone. Most installations are deployed on man-made waterbodies such as irrigation dams, industrial basins, water treatment plants and unused mining pods. The major cost components of a floating solar installation are: floating platform 28-35 % and PV modules 35-40 % [Acharya – TERI]. Today, most floating solar installations are in locations of wave category 1. For locations with higher waves some initial studies and pilots are underway.

Type of activity and TRL

- Floating solar on smooth water (TRL 8): activities needed on data collection on performance and O&M and on cost down driven design optimisation.
- Floating solar on wave category 2 waters (TRL 6): activities needed to optimise the system designs for performance, lifetime and cost.
- Floating solar on wave category 3 waters (TRL 4): activities needed to study the feasibility in demonstration and pilot projects.
- Floating solar on wave category 4 waters (offshore) (TRL 3): activities needed that model the different conceptual approaches including scale model testing.
- Develop and verify predictive yield models including dynamic behavior of the PV including floats, temperature effects and wave induced mismatch losses, depending on the application environment (wave height class).
- Develop and verify components with proven lifetime and reliability for the various application environments.
- Develop design rules for systems with proven neutral or positive ecological impact.
- Develop system designs for near-100 % circularity, including the floating platform.
- Develop effective grid systems for floating solar in conjunction with wind energy and/or storage.

Oceans of Energy's offshore solar system at North Sea. © Oceans of Energy.

KPIs

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
System Design	Alignment with existing PV standards and develop new standards where needed. (2025) Components (modules and electronics) with proven >20-year lifetime in floating solar applications, especially for application in salty environment and under the impact of continuous movements (2027) Optimised system designs (performance, lifetime, ecological impact and cost) for the subsequent wave categories (2030) System designs with incorporated near-100 % circularity (2030)
Modeling	Performance models with high accuracy yield predictions that include the specific effects of cooling and system movements (2025)
Installation	Offshore floating solar installations for application in conjunction with an offshore wind farm, with optimised synergy on electrical infrastructure, spatial planning and O&M (2027) Bankability of floating solar at the level of standard solar parks, by a systematic build-up of data on performance and O&M (2030)

Roadmap 5: Infrastructure Integrated PV

Rationale for support

With infrastructure integrated PV (IIPV) we mean the integration on or into infrastructural functional objects such as road pavement, noise barriers, crash barriers, dikes, landfills, flyovers and road roofing. In all these applications, the *primary functionality* of the infrastructural object is leading. This primary functionality may be safe traffic, safety against flooding, waste storage or noise reduction. The challenge for the development and implementation of IIPV is to design integrated solutions that are technically and economically feasible.

Status

A modest amount of IIPV projects on landfills and into noise barriers have been realised, and even fewer on IIPV in crash barriers, flyovers, road surfaces, dikes and road roofing.

Targets, Type of activity and TRL

- Solar noise barriers (TRL 7): activities on pilots and demonstrations, including O&M monitoring, cost effectiveness studies and performance model development.
- Solar crash barriers (TRL 4): feasibility studies and pilots, including safety & event analysis studies and performance model development.
- Solar integration into roads (TRL 7 for light traffic, TRL 4 for heavy traffic): activities on pilots and demonstrations, including cost effectiveness studies, safety & event analysis, feasibility of new concepts and performance model development.
- Solar installations on dikes (TRL 5): feasibility studies, pilots and demonstration studies, including dike O&M aspects, safety & event analysis and performance model development.
- Solar installations on landfills (TRL 6): pilots and demonstrations for new mounting concepts (not penetrating the waste covering foils and layers), including lifetime studies, safety & event analysis. and performance model development.
- Solar integration into road roofing (TRL 6): Pilots and demonstration studies, including cost effectiveness studies and performance model development.

KPIs

KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Optimised System Design (Performance and Cost)	Across Functions: Noise reduction: solar noise barriers that can be applied irrespective of road orientation Safety: solar crash barriers along highways, solar integrated into pavements and road roofing Safety Against Flooding: installations on dikes Safe Waste Storage: installations on landfills

PV together with small batteries can power wireless sensors or actuators, including in the home.

Roadmap 6: “low-power” energy harvesting PV

Rationale for support

Sensors or actuators in dim places (e.g. indoors, or receiving only artificial or diffuse light) may be powered by a combination of a suitable PV cell and battery.

Status

Mass-market PV technology, tuned to the solar spectrum and bright light, is not adapted to dim conditions. Currently, amorphous silicon PV is widely used for indoor and portable applications with commercial efficiencies of around 10 % on devices fabricated on glass. Although compound semiconductors have achieved higher power efficiencies, their cost limits their commercial rollout for commercial products. New generations of PV technologies have shown great potential in harvesting energy in low light conditions and lab demonstrations up to 30 % efficiency values have been shown for artificial indoor illumination.

Targets, Type of activity and TRL

- Fabrication of large area device for demonstration of new applications powered by PV energy harvester such as IoT, remote sensing and home automation applications (TRL6).
- Bring the technology from TRL3-4 to 5 or 6 for PV technology on new functional substrates (flexible, paper etc).
- Integration between different energy harvesting and with storage systems (TRL 6).
- LCA analysis of internet of things or wireless sensor systems with and without indoor PV to understand benefits and limitations.
- Encapsulation materials and designs for guaranteeing product lifetimes (wide range of TRLs, from new concepts to utilizing existing ones for solar PV as well as that of electronics).
- Bring together developers of PV technology, with storage, power, sensor, electronics developers, as well as operators of smart cities, smart products, and other stakeholders to develop better lower power electronic systems (TRL 6-8) and totally new concepts (TRL 1-3).

KPIs

There is no specific standard for performance quantification under low-light conditions. The efficiency and hence the power density output is strongly dependent on the spectrum, especially since the calibration is usually done in lux. The variability of the light conditions implies the development of efficient electronics that could gather all the energy produced by the light harvesting system. At the same time, integration with a device integrated or system integrated storage element can provide the power continuity needed in some low power applications such in IoT or remote monitor sensor. The pervasiveness of low power PV energy harvesting requires green non-toxic material and an appropriate waste management/recycling. In this context, one can define some specific KPIs:

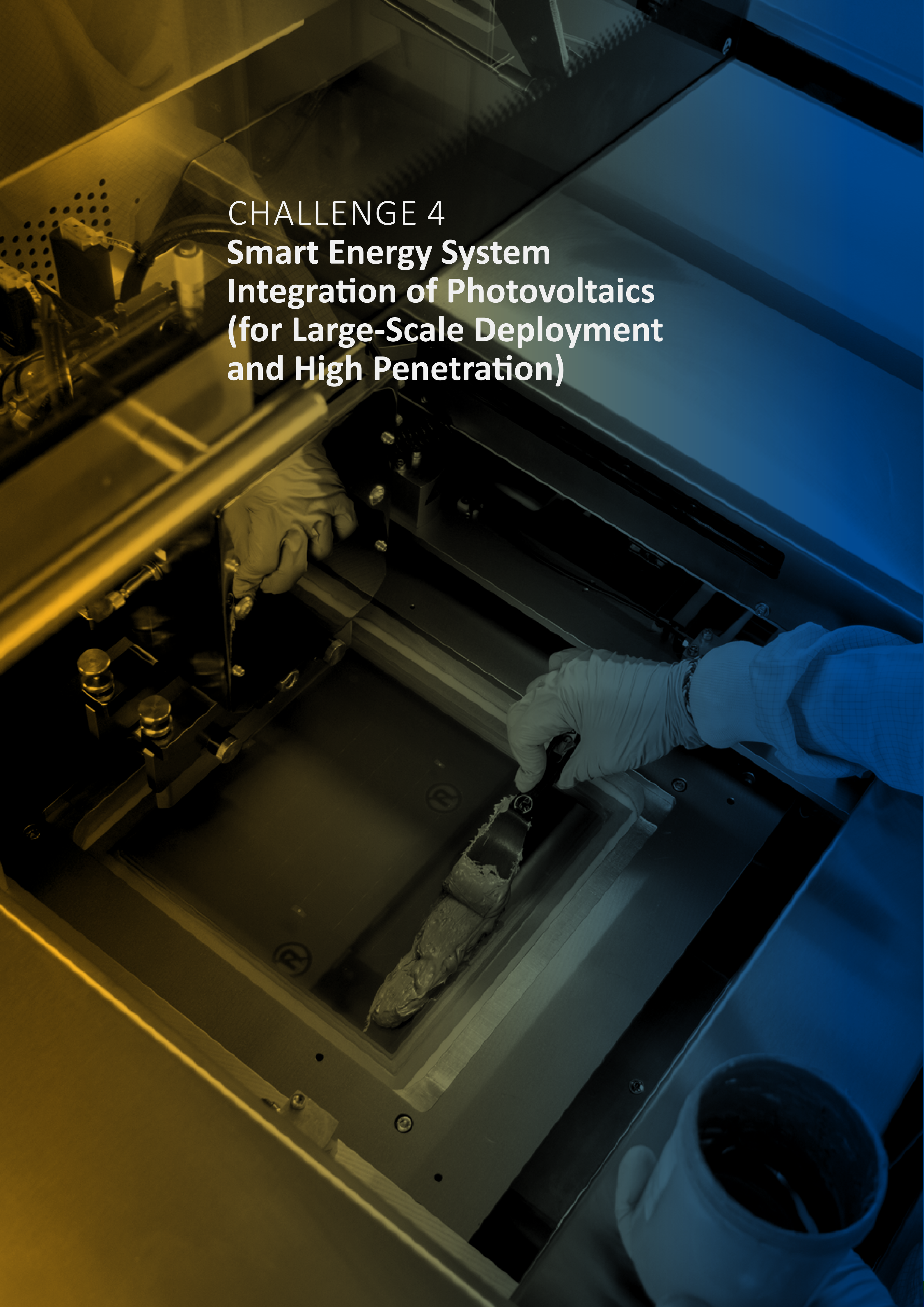
KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Design and Fabrication	Identification of PV materials and PV architecture for the specific low power applications depending on the light intensity, light spectrum and application itself (2025) Module/cell design and fabrication process that enables easy tailoring of the PV device to products specifications (2027)
Performance	Power and energy yield PV performance to meet application specific power and energy requirements (2027) Reproducibly achieve 25 % efficiency or more over module level in the 200 lx-500 lx under white light illumination (2027)
Manufacturing	Cost of the PV energy harvester compatible/comparable with the cost of low power electronics (2027)

Photovoltaic Roofing for Motorways: Concept and deployment of a demonstrator for the generation of solar energy in the road infrastructure. The Photovoltaic Road Roofing demonstrator will be implemented in 2022.
© AIT and PV-SÜD project (concept) →

CHALLENGE 4

Smart Energy System Integration of Photovoltaics (for Large-Scale Deployment and High Penetration)



PV is growing strong in independent applications at all levels and complexities: on roofs or façades of buildings for domestic and commercial use, for commercial systems of various sizes up to utility size connected to the transmission system providing non-dispatchable energy to the system managed by the operators of the integrated grid.

Objective 1: Energy system integration

The integration of the energy system that can form the basis of the targeted energy transition will be built on the interdependency of all the energy vectors that can seamlessly contribute to the interconnected grid for optimal use of the available sustainable resources. It will allow the effective integration of the variable, non-programmable RES, which will be the predominant energy sources after 2030. PV is a vital contributor in this energy mix with the added advantage that it can be sited everywhere, most importantly on buildings and developed areas where the actual load is, therefore directly contributing to the optimal use of resources. Key factors for the success of this transition are embedded in the smartness of enabling technologies through the digitization of all constituents with distributed control responding where needed to make the paradigm change of load following generation instead of generation following load a reality.

The document “A clean Planet for all” [(80)] strengthens the view that the most important single driver for the transition to a de-carbonized energy system is the growing role of electricity, both in the supply of alternative fuels and in the final uses. This will imply, however, a paradigm shift to energy resources that are sustainable by nature but largely meteorologically driven. Hence, energy system integration grows in importance requiring the services of technologies such as storage as a key enabler, both at a central level and distributed for flexible consumers. Flexibility at all levels is of growing importance transforming demand into a key enabler for optimal use of resources bringing the end users into prime providers of flexibility. Spatial planning and the necessary citizen and local authorities’ engagement makes the PV resource vital and necessary for meeting the energy needs of tomorrow exploiting to the full the low-cost solutions that PV systems provide.

More than 714 GW of solar PV power plants have already been installed worldwide [REF: IRENA latest report], making solar PV the number two renewable electricity source and catching up Wind power plants as current number one. A substantial portion of the PV installations in Europe until

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(80) *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. EUR-Lex- 52018DC0773- EN- EUR-Lex (europa.eu)

← View into screen-printing equipment.© Fraunhofer ISE now are related to the randomness of feed-in tariffs established by local governments in the first wave, while the second wave of deployment is driven by the net-metering and self-consumption. As priority dispatch for new PV installations is expected to prevail in all EU countries, in the near future (it is already a market obligation in countries of the south such as Cyprus and Greece) the spread of PV systems including integration in buildings could represent a new stable driving force for the diffusion of PV systems. The trend suggests a capillary widespread of RES mainly through small to medium PV plants right in the residential sector capable of providing the energy resource for energy communities to flourish.

PV is growing strong in independent applications at all levels and complexities: on roofs or façades of buildings for domestic and commercial use, for commercial systems of various sizes up to utility size connected to the transmission system providing non-dispatchable energy to the system managed by the operators of the integrated grid. All these solutions are being operated as energy sources and complimented with enabling technologies such as storage where required by local rules or tariffs to make them dispatchable and grid supportive as required. However, in the years ahead PV systems should be looked at as active contributors of the integrated grid utilizing dependable forecasting tools that are openly available as a cloud service or otherwise for wider use (both serving day ahead optimal planning but also during intraday dispatch needs based on a two hour ahead rolling to facilitate optimal resource use) for improving the reliability of the complete system. For this reason, in this SRIA the R&I needs for developing the integration solutions of PV systems under the following operational regimes are detailed to be addressed in the forthcoming calls of Horizon Europe and other complimentary financial instruments both European and national:

- More intelligence in distributed control
- Hybrid systems including demand flexibility (PV+ Wind + Hydro with embedded storage + batteries + green hydrogen/fuel cells + solar fuels/gas turbines & demand management)
- Aggregated energy and Virtual Power Plants
- Improved efficiencies by integration of PV-systems in DC-networks

Roadmap 1: More intelligence in distributed control

Rationale for Support

The penetration of RES in the energy mix of Europe is growing fast and its intermittent nature calls for smart solutions utilising supportive enabling technologies that can safeguard the quality, reliability and resilience of the interconnected grid that is emerging. This is a growing need due to the transformation that is taking place on the distribution grid, going more active and moving away from the past unidirectional flow of energy from generating stations to load centres far away.

The rollout of intelligence on the distribution network generates the required data for building distributed control in support of the wider system. This is a much more responsive to the needs of the interconnected grid and avoids delays in taking corrective action, making the system more reliable and resilient.

Status

Currently the intelligence provided on the distribution system is limited to the following services:

- Forecasting tools for providing an estimate of the anticipated energy the following day but not adequate for long term planning or operational dependence for the day reserves of the system.
- Smart inverters providing voltage support and quality of supply at point of common coupling of the RES systems meeting the connection and operational requirements of the operators.

Targets, type of activity and TRL

This roadmap aims to add intelligence to the PV systems to be responsive to system needs through the following targets:

- Develop advance accurate forecasting of PV production at different spatial and time resolutions depending on targeted market (day ahead, intraday or actual day dispatch) by means of intelligent physical modelling and data analysis capable of supporting the intraday, day ahead and long-term planning and operation of systems as an enabling functionality for optimal control in the constantly growing RES sustained energy system.

- Add hardware / software intelligence to PV for making it ready for smart integration into the energy system of the future, e.g., PV inverters of different size (small/string/large) with added sensors capturing VAR and Watt quantities, voltage magnitude and quality at their point of common coupling or advance features of inverters including the capabilities of grid forming inverters capable of actively contributing to the needs of the integrated grid, responding to the growing family of IoT for energy management in an active distributed system including energy communities. This added intelligence and controllability will enable the completed PV system to offer grid support in managing quality of supply including voltage control, flickering, frequency fluctuation, contribute to virtual inertia/ synthetic inertia etc.

- Planned activities for developing the required intelligence in complete PV systems with peripheral equipment are the following:

  – Action 1: Technical and software development for improving PV system forecasting capabilities in combination with storage moving TRL from 6 to 8 by 2025.

  – Action 2: Technical development of inverter intelligence for providing frequency control moving TRL from 6 to 8 by 2025

  – Action 3: Technical development of inverter capabilities for providing the grid forming capabilities moving TRL from 5 to 8 by 2027.

KPIs

Possible KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Forecasting tools for PV systems to be widely available as an open access through cloud or otherwise, a service that can be accessible by all	By 2025: day ahead accuracy of 95 % for 95 % of the cases.
Forecasting tools for PV systems to be widely available as an open access through cloud or otherwise, a service with storage of 8 % of energy generated within the planned day	By 2025: day ahead accuracy of 99 % for 99 % of the cases.
Smart inverters to be supportive to system frequency control	By 2027: at least 5 % of the generated energy and 50 % of ground-based PV plant inverters to be equipped with grid forming functionality.
Grid forming capabilities of smart inverters to be operational	By 2030: at least 90 % to facilitate building energy management systems for improved security of supply to all connected users.

Roadmap 2: Improved efficiencies by integration of PV-systems in DC-networks

Rationale for support

The presence of DC grid is becoming evident as more and more sources and systems in the integrated grid are DC reliant. PV generation is DC based but primarily it is transformed to AC for storing or use even though applications to a great extent are DC operated. This reality is generating the obvious question as to why generated energy is converted to AC for use. This approach is generating transformation losses that can be avoided if energy is directly used in the physical form that is initially generated i.e. DC.

Status

The AC grid is still currently a highly interconnected system dependent on centrally generated energy away from load centres, that is either directly generated or transformed to AC to achieve long distance transmission to reach economically the end users. However, distributed DC generation is rapidly growing and is used on our roofs, yards or other premises that are nearby load centres. Moreover, battery systems, electric vehicles, heat pumps and others are directly DC operated or they are more efficient when they are operated in DC. Direct use of the DC energy generated is an obvious choice, thereby avoiding costly conversions.

Targets, type of activity and TRL

The objectives of this roadmap include developing systems and solutions for which PV as the energy source is directly connected to DC driven systems to achieve improved efficiencies. The following targets are anticipated:

- Combining batteries with PV for minimizing inverter costs and improving overall system efficiencies. This requires optimal sizing of systems for lowest cost both in capital investments and operational costs. Sizing of storage systems will be quantified in relation to the wider needs of the interconnected system leading to low-cost aggregated systems for the DSO, energy communities and end users. Based on vehicle to grid technologies, EV batteries as well as stationary batteries can be used to support flexibility and grid management. This exercise will lead to defining optimum battery /PV capacity depending on demand for households, energy communities or large-scale systems etc.

- Combined systems using DC where possible to the highest degree of integration (ex: PV+ heat pumps + EV charging + electrolysers etc) including DC to DC EV charging where it is economically viable adding power when required for faster charging and flexibility to the system for optimal use of resources for the benefit of the integrated grid. The integration of PV plants with HP and storage systems including thermal storage where optimal solutions favour such options, can increase the share of self-consumption of energy produced with minimum impact on the electrical AC grid. However, sizing is a wider issue and this calls for a system approach that energy communities, aggregators and wider service providers will optimise for the benefit of all interconnected users.

- Use of AC+DC and DC only microgrids, as well as DC-coupling between these microgrids and main grid supplied primarily by PV systems that can play an important role for increasing energy resilience and efficiency, reduce impacts on transmission grids by PV integrated in such microgrids (more predictability to main grid, less required flexibility, less inertia depreciation, etc.).

Planned activities for developing the required DC or hybrid AC / DC system solutions based on PV as the source of energy are the following:

- Action 1: Technical development of DC systems for providing heating, cooling, hot water and DC appliances in buildings using PV as the resource moving TRL from 6 to 8 by 2025

- Action 2: Commercial development of DC systems for providing heating, cooling, hot water of buildings using PV as the resource moving TRL from 6 to 8 by 2027.

- Action 3: Technical and commercial development of DC or AC/DC hybrid systems to meet the needs of energy communities for providing heating, cooling, hot water, DC appliances and e-mobility using PV as the resource moving TRL from 6 to 8 by 2027.

PV in Buildings. © Solarwatt

KPIs

Possible KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Systems to be commercially available for providing heating, cooling and hot water directly from DC powered systems relying on PV as the source of energy	By 2025: efficiencies surpassing 20 % compared to AC alternatives
The hybrid AC / DC systems in buildings based on PV as the energy resource.	By 2027: to be the norm in new buildings with DC covering the needs for heating, cooling, hot water and e-Mobility
The hybrid AC / DC energy community systems resourced primarily from PV systems.	By 2030: achieve 30 % improved efficiencies using DC as the prime source for heating, cooling, hot water, DC appliances and e-Mobility

Roadmap 3: Hybrid systems including demand flexibility (PV+ Wind + Hydro with embedded storage + batteries + green hydrogen/fuel cells or gas turbines etc.)

Rationale for support

RES systems are by nature highly dependent on the variability of the source that drives them. This variability characterises the generated energy resulting in a variety of problems to the system and the operators. At low penetrations of RES the inherent variability is easily absorbed by the generation systems that rule the energy mix and take the operational roles for balancing continuously the system without any problems transferred to the end users. In the case of CSP systems with the inherent storage, the cost of the system hinders its wider use due to higher LCOE price from the prevailing energy mix of countries.

While low penetrations of RES easily absorb variability, as RES penetration grows the variability becomes more pronounced especially in weak links and island systems. To improve on the above eventualities, developers have surged the possibility of building hybrid systems aiming to address the following issues:

- Improve on the variability by mitigating it with combination of the various sources hence cancelling each other to a great extent.
- Adopt the generation profile of Hydro power plants with generation coming from PV systems and combine it other storage/generation systems (batteries, green hydrogen, solar fuels).
- In specific locations (e.g. Northern Africa) combine the generation profile of CSP system with generation coming from PV systems a hybrid profile that meets all the requirements of operators to be dispatched. This system is much cheaper to generate and uses the controllable CSP energy to absorb any variability coming from PV systems.

Status

Currently RES systems are lightly hybridised to gain the benefits of building on individual strengths. PV has been linked with systems with embedded storage to raise dispatchability and lower the cost of the complete system building on the strengths of embedded storage and the low-cost availability of PV systems. Thus, systems are developed combining PV with storage or PV with other RES to serve very specific projects. PV is mostly linked with storage to improve energy management in buildings thus gaining on specific terms of tariffs or with other RES to offer a lower cost energy to the system.

Targets, type of activity and TRL

The objective of this roadmap is to develop systems and solutions for which PV, as an integral contributor of interconnected systems, can offer hybrid solutions that better meet needs of the integrated grid. The following targets are anticipated:

- Hybrid inverter solutions including the smartness of the system infrastructure can offer maximum use of local resources for the collective benefit of the system and the connected users. This can be extended to include hybrid solutions with floating PV on reservoirs in combination with hydropower.
- Hybrid systems meaning PV in combination with wind and other available RES, can offer higher efficiencies. This calls for a careful system approach capitalizing on local resources with available enabling technologies such as storage, V2G EVs, smart grids, or demand flexibility to minimize system cost for the benefit of system and users. These solutions will include specific PV-related challenges for P2X for achieving higher all-round efficiencies (where X = heating, thermal energy, fuels, feedstocks etc).
- The above solutions will operationally require the services / advantages that grid forming inverter technologies offer with the added functionalities and intelligence to respond effectively to the interconnected system needs in line with adapted policies.
- For improved operational and financial benefits of these hybrid systems, aggregated portfolios will be required to efficiently provide the resource availability through the prevailing market rules allowing optimal controllability of available resources with the supportive technologies like smart systems and solutions, batteries, EVs, demand flexibility etc to maximise overall system benefits and hence the achieved revenues for the benefit of all contributors.

PV in Buildings. © Viridian.

Planned activities for developing the required hybrid systems and solutions based on PV as one of the primary sources of energy are the following:

- Action 1: Technical development of hybrid RES solutions for providing competitive energy using PV as one of the primary sources of energy moving TRL from 6 to 8 by 2025
- Action 2: Technical development of hybrid RES solutions in combination with external storage systems for providing competitive energy using PV as one of the primary sources of energy moving TRL from 6 to 8 by 2027.
- Action 3: Technical development of hybrid RES solutions using the flexibility of load including external storage systems and EVs for providing competitive energy using PV as one of the primary sources of energy moving TRL from 6 to 8 by 2030.

KPIs

Possible KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Hybrid RES solutions to be developed for capturing the benefits of low-cost PV systems by absorbing the variability of the solar resource	By 2025: offering an LCOE price of the combined system lower than the prevailing wholesale price of countries and islands in southern Europe.
Hybrid RES solutions to be developed using the added benefits of storage systems offering combined solutions with PV systems	By 2027: LCOE price of the combined system lower than the prevailing wholesale price of countries and islands in EU.
Hybrid solutions to be developed using in addition the flexibility of load including storage systems and EVs supported by the advance features of smart inverters	By 2030: grid to offer complete systems serving energy communities throughout the EU at lower LCOE price from the country average.

Energy communities, aggregated systems, Virtual Power Plants in combination with a portfolio of resources and users can be the collective emerging system that will facilitate the energy transition to the low carbon economy.

Roadmap 4: Aggregated energy and VPPs

Rationale for support

The new directives springing from the Clean Energy Package of the EU aim at setting fundamental principles for well-functioning, integrated electricity markets, which through appropriate mechanisms facilitate aggregation of distributed demand and supply. Moreover:

- Market participation of consumers and small businesses shall be enabled by aggregation.
- Customers should be allowed to make full use of the advantages of aggregation of production and supply over larger regions and benefit from cross-border competition.

It is aimed through this upcoming legislation that aggregators are expected to play an important role as intermediaries between customer groups and the market.

The combination of these aspects clarifies the important role of aggregation in the future energy market, calling for aggregators to act as enablers for consumers/prosumers in respect of their access to the energy market addressing issues like:

- Aggregation and demand response
- Aggregation and citizens /local energy communities
- Self-consumption and local settlement of generation
- Aggregation and market participation
- Balancing services
- Meeting the aggregated needs of communities connected to the grid or in an islanded mode

Status

Distributed generation with its dispersed nature currently operates independently through dedicated tariff systems that vary between member states. Aggregators have been introduced in the market and technically have approached dispersed generation through portfolio of solutions aiming to raise the benefits to the providers of the dispersed generation. This approach introduces technology solutions like Virtual Power Plants (VPPs) capable of contributing to the day-to-day operation of the system and has managed to convince this role and some member states have given market rights for their participation. + Dawn of ENERGY Communities.

Targets, type of activity and TRL

The objective of this roadmap is to develop systems and solutions for which PV as an integral contributor of distributed generation can be pivotal in building functional energy communities aggregated and operated through advance distributed controls in hierarchical set up with the integrated grid. The following targets are anticipated:

- Energy communities, aggregated systems, Virtual Power Plants in combination with a portfolio of resources and users can be the collective emerging system that will facilitate the energy transition to the low carbon economy. Through this approach solutions can effectively address the need for overcoming energy poverty, support energy democracy, expand cooperative solutions in utilizing local energy resources for the collective benefit of providers and users. Peer to peer trading and use can be made feasible and emerging solutions highly attractive and implementable.

Hierarchical control of the interconnected grid is the way forward for maximizing the benefit of distributed resourc-

PV in Buildings. © Zigzag

es and intelligence provided by the digitalised energy grid. System support can be exploited to the full thus minimising the cost of the interconnected system for the benefit of all connected users. This calls effective protocols and robust communication and cooperation between the various required levels of control that is cyber secure, through the emerging interoperable and observable system offering the benefits of the advanced features of smart power electronics, sensors and intelligent systems.

Planned activities for developing the required hybrid systems and solutions based on PV as one of the primary sources of energy are the following:

- Action 1: Technical development of the portfolio of tools for aggregators moving TRL from 6 to 8 by 2025
- Action 2: Technical development of standardised operational models of energy communities moving TRL from 6 to 8 by 2027.
- Action 3: Technical development of hierarchical control of the integrated grid moving TRL from 6 to 8 by 2030. The adaption of this hierarchical control to be extended to support islanded mode of operation if added security is required.

KPIs

Possible KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
A portfolio of tools to be available for the functioning of aggregated distributed generation	By 2025: capable of offering collective services to the system.
Standardised operational models of energy communities to be available	By 2027: facilitating the setting up and the operation of energy communities as defined in the electricity directive.
The required hierarchical control of the integrated grid to be standardised	By 2030: facilitating the operation of energy communities in full compliance with the grid rules and the requirements of DSOs and TSOs.

Roadmap 5: Interoperability in communication and operation of RES smart grids

Rationale for Support

Due to the lack of common rules, country specific grid codes, standards and interconnection rules, different communication approaches and protocols are used and therefore quite often installation/energy application is different. The design and engineering effort therefore is quite high. Also, the scalability of such solutions suffers, calling for modifications and adaptation with added complexity and cost.

The following main problems exists today related to ICT solutions for Smart Grids with a high share of DER:

- Missing common application modelling concepts for power and energy systems,
- No existing model-based engineering concepts for energy applications in heterogeneous, distributed environments,
- Scalability and openness in Smart Grid solutions with a high share of DER components only partly addressed,
- Lack of common and open communication interfaces in Smart Grids impede scalable and distributed automation solutions,
- Missing possibilities to update and extend DER functions and ancillary services,
- Available proprietary automation solutions in Smart Grids prevent efficient reuse of control software, thus the engineering costs exceed admissible costs by far,
- Lack of cyber-security of DER devices (i.e. cyber-security protection means are partly missing)

Status

Currently, the availability of ancillary services (e.g., local voltage and frequency control) provided by DERs (e.g., PV-inverters) enables local energy control. For instance, local voltage control using reactive power is commonly available. If active, such a local voltage control function tries to keep the voltage at the Point of Common Coupling (PCC) at a level usually specified by a characteristic curve. Most of the PV-inverter manufacturers provide some kind of interface to their inverters (mainly proprietary protocols and data models) where the characteristics of the control can be specified and/or adapted.

If the local DER control is active, the area of influence voltage (and many other physical parameters) can be controlled in the power distribution grid. However, without coordination, the operation of the whole grid may be sub-optimal. In order to achieve a global optimum, a coordinated distributed function is necessary.

Targets, type of activity and TRL

The massive deployment of distributed generators from renewable sources in recent years has led to a fundamental paradigm change in terms of planning and operation of the electric power system and its grid. Smart Grids are one of the most promising solutions to use the existing grid in a more efficient way, thus allowing higher penetration levels of renewables. To capture the benefits of such intelligent power grids, it will be necessary to develop new information and communication solutions, automation architectures and control strategies. That opens the ability to effectively manage the large numbers of dispersed generators and to utilise their “smart” capabilities. However, up to now a common and formal modelling concept for energy applications used in Smart Grids and distributed energy resources is still missing. Moreover, the scalability and openness of today’s utility automation systems that handle a high number of distributed generators needs to be improved due to the lack of common and open interfaces as well as the usage of a huge number of different protocols.

Future inverter systems need to be interoperable from the automation/control and communication point of view and they should provide advanced services including auto-configuration of PV plant components.

There is still a lack in the harmonization of PV plant control and the access of power grid operators since domain standards like Modbus/Sunspec or IEC 61850 for remote control are partly implemented by vendors. Another issue is that vendors usually use proprietary solutions for monitoring. Moreover, an ICT framework to model and implement local but also distributed/remote control strategies in an easy manner is also not possible. Therefore, changing grid codes, standards, interconnection rules for DER and changing requirements cannot be quickly addressed in a complex, distributed Smart Grid system environment.

Digitalisation can provide architectures, concepts and methods for the creation of a truly open and interoperable information and automation solution for the integration of renewable energy sources into Smart Grids. Moreover, it can also help to define a kind of an access management for distributed energy resources, which takes different user roles in the Smart Grid into account and therefore make such a system more robust and resilient against cyber-attacks.

Based on the above outlined shortcomings and open issues of currently available approaches, the following topics need to be tackled[35]:

- Develop interoperability on inverter level for fully integrated and connected systems.
- Develop connectivity with various communication protocols to allow for appropriate functionalities in different system applications (not all protocols have the same level of complexity and functionality, such as Modbus/Sunspec or IEC 61850).
- Integration of 3rd party applications on inverter platforms, allow for additional software components, e.g., forecasting, energy trading functions, remote controllable functions and services.
- Develop cybersecurity schemes for interconnected and controlled PV systems.
- Develop reliable and redundant communication systems for mission critical applications.
- Planned activities for developing the required interoperable smart grid systems with trustful communication systems are the following:
  - Action 1: Technical development of interoperable control systems of inverter-based solutions moving TRL from 6 to 8 by 2025
  - Action 2: Technical development of communication protocol connectivity of system applications moving TRL from 6 to 8 by 2027.
  - Action 3: Technical development of for the interoperable integration of third-party applications in the inverter platforms moving TRL from 6 to 8 by 2030.

KPIs

Possible KPIs that can be utilised for capturing progress in the above identified R&I fields are:

KPI	Target Value
Build a resilient, open automation and control architecture for inverter-based DER	By 2025 to be operational
Develop accessible source-based reference implementation of an open automation architecture	By 2025 to be operational
Develop a role-based access management for inverter-based DER	By 2025 to be operational
Fully interoperable advanced (remote controllable) inverter services with standardized and safe/resilient communication protocols	By 2027 to be operational

CHALLENGE 5

Socio-Economic Aspects of the Transition to High PV Contribution

Solar photovoltaics is one of the key technologies in one of the seven flagship areas for investment and reform "*Clean Technologies and Renewables*". The massive and rapid deployment of additional renewable energy, and in particular solar energy capacities needed for the energy transition and fostered through the recent political framework will only be possible, however, if a broad public and political support can be maintained when solar energy becomes a visible part of every person's living environment, both in urban and rural areas.

Since several big societal challenges and trends require (additional) space to be addressed, such as the energy transition moving towards sustainable agriculture, increasing biodiversity, providing sufficient housing, careful balancing of very different and sometime competing societal costs and values is key to success.

Europe should put itself at the forefront of large-scale deployment, ambitious technological development and advanced manufacturing, sustainability of production, quality and efficiency of solar products and the development of business models that capture PV's value. These are the fact-based reasons for the **high PV scenario** [(81)] that will substantially contribute to the European Green Deal, Climate protection goals and the European recovery and resilience plan.

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(81) High PV scenario- Solar Power Europe: https://www.solarpowereurope.org/100-renewable-europe/

← The gas panel of the Si epitaxy reactor "PEpi" for process gas regulation and control. © Fraunhofer ISE

↑ PV in Buildings. © Viridian.

Socio-economic aspects for the "high PV scenario"

The energy transition offers great benefits and opportunities, but also poses major challenges to society. Success of the transition depends heavily on its capability to demonstrate the benefits for individuals, companies and society as a whole, while addressing and mitigating the challenges effectively, in a well-balanced manner. For example, the societal benefit of renewable energy generation, linked with the challenge of visual impact on the living environment, can influence the feeling of well-being of individuals. Another challenge is minimizing generation costs versus optimising ecological effects of solar parks. Addressing these cases can generally be described as optimising the sum of societal costs (monetary, aesthetic, ecological, etc.) and benefits or values (mitigation of climate change, jobs & income, living comfort, etc.). Since it is often not easy, or even not possible to quantify part of the societal costs & benefits, it is important to understand the underlying drivers and how they depend on actions that can be taken. For instance, under which conditions may people accept or even appreciate solar parks in their living environment? Or: what is the allowable extra cost for an eco-positive solar park? These, and many other questions, require dedicated socio-economic research, in addition to the technology development and deployment initiatives.

Socio-economic impacts of the energy transition with high PV scenario should be addressed as joint action for all RES, especially partnering of Solar PV with Wind and Storage - Green Hydrogen and Batteries. New quality jobs creation, both upstream and downstream, technological and energy independences (reducing the dependence on energy imports) should be covered in activities to raise awareness of all the benefits that PV brings, enhancing and ensuring societal acceptance and further strengthening citizen and public engagement and support for the high PV scenario. More generally, comprehensive Societal Cost-Benefit Analyses are needed to find the optimum path of the energy transition with a large share of PV; 'optimum' referring to energy, economy, ecology and society.

Europe should put itself at the forefront of large-scale deployment, ambitious technological development and advanced manufacturing, sustainability of production, quality and efficiency of solar products and the development of business models that capture PV's value.

Objectives

1. Higher awareness of solar PV-related externalities and benefits

Based on competitiveness, sustainability, energy independency, PV can be the key enabler for the sustainable energy transition, especially with a new way of integration of PV technologies (dual function of land for Agri-PV, BIPV, use of build space like parking spaces, roads etc.) and create awareness for additional electricity needs due to sector coupling (mobility, heating, H_2 in industries, desalination, hybrid generation and coupling with other energy sources).

Wide societal involvement and participation for solar PV deployment

PV is a renewable energy technology which can be employed by everyone. Facing the urgent need to increase renewable electricity generation to meet the goals of the European Green Deal and the climate protection goals of the Paris Agreement, it is a logical step to utilise PV technology on a wider scale.

Nowadays, PV benefits from widely spread high technology acceptance in relation to all existing renewable energy technologies. Nevertheless, when looking at figures for implementation, the implementation of PV on a regional or local level does not coincide with the wide-spread high technology acceptance of PV. Reasons behind this paradox is a gap between technology acceptance and the efforts which anyone has to put into the development and execution of PV implementation until it is operational. Therefore, increased involvement and direct participation of all stakeholders must be a major objective for the years to come. The relevant stakeholders (private/ commercial investors, installers, municipal/regional planning authorities, grid operators etc.) want simplification of regulations, the end of permissions and opportunities to deploy PV for individual or collective supply. Accordingly, research has to extract and disseminate factors increasing the attractiveness for implementation, procedures that simplify implementations will be key. The objective is to design conditions which go beyond acceptance but enable that implementing and employing PV electricity become self-evident like buying new shoes.

Developing a PV hotbed for urban implementation

PV is the only renewable energy technology that can enable renewable electricity generation in urban and highly dense spaces throughout Europe. This has been acknowledged in smart city strategies from EU and member states. Cities and urban regions will be one of the major boosters to increase the implementation of PV within the current decade. Therefore, Europe needs to provide a kick-start for initiatives which design regulatory and administrative environments for cities, regions, energy communities to increase the implementation of PV to 25 % or more of the total electricity demand. Collaboration between scientific and municipal stakeholders can bear the requirements for

The next decade is crucial for the success of energy transition and an accelerated deployment of PV, because any new investment in fossil power generation over this timespan will otherwise become a stranded asset later and increase the societal costs.

citizens and suppliers to make quick progress towards solar cities and solar energy communities. Accessibility to financing and crowdfunding solutions have to be aligned to support progress and urban economies. National regulatory bodies have to be involved in research and transfer, as legislation in European member states will be crucial as enablers for making PV in urban territories a game changer in the fight against global climate change - through their potentials of the existing roof spaces, PV in double space use on parking and other useful areas, by activation of building owners, companies and the PV business sector.

2. Economic & sustainability benefits

The roll out of PV installations create jobs. In Sweden it has been shown about 10 full-time labour places per installed MW [82] (on yearly basis, on a national average) are created in the down-stream sector, which contain actors such as installers, retailers, utilities, consulting firms and real estate owners. These jobs created in the installation phase are spread between low educational jobs (such as fitters), medium educational jobs (such as electricians) and high educational jobs (such as computational engineers). In addition to job creation in the installation phase, the number of people needed for operation and maintenance will increase as the cumulative PV capacity grows and the age of the running PV systems increases. Worldwide employment in the solar PV industry was estimated at 4 million workers in 2020. Solar PV employment in all of Europe is estimated at 239,000 jobs in 2020; and could consist of 19.9 million jobs worldwide by 2050. [83] In 2020, the solar sector created around 357,000 direct and indirect jobs, and solar sector jobs are predicted to grow to 584,000 positions in 2025. [84]

If the shares of PV components manufactured increases as a result of a revival of the European solar industry, more than 100 000 jobs [85] in the up-stream PV sector could also be created. The upstream sector encompasses both low educational jobs (such as factory workers) and high educational jobs (such as process and development engineers). The supply of competence is a key parameter for the social acceptance of PV as it creates jobs for the society and also ensures higher quality products and installations by well-trained workers. Well-functioning products that deliver as promised and do not break down are important for the general acceptance of any technology. High quality education and training programmes including certification are therefore important socio-economic factors for PV.

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(82) https://iea-pvps.org/wp-content/uploads/2020/08/NSR_Sweden_2019.pdf
(83) IRENA, Renewable Energy and Jobs Annual Review 2021
(84) SolarPower EU Solar Jobs Report 2021
(85) https://www.meyerburger.com/fileadmin/user_upload/Whitepaper/Solar-Production-in-Germany_WhitePaper_MB-SMA.pdf

Paradigm shift in public support - from declarative to on-spot actual support

General declarative support for PV exists by goals and masterplans. Now it is the time to create actual support for a massive deployment of PV - especially in urban areas. Until now, implementing PV has been permissioned by local or regional authorities. In the coming decade the responsibility of policy from national to local level and regulatory framework has to change from permission of PV towards enabling and requirement of PV. Good practices appear on the horizon (City of Vienna PV obligation for public buildings, federal state Baden-Württemberg PV obligation on parking spaces etc.) and have to be adopted widely. Market regulation must be re-balanced to release the existing implementation potential, raise public support and accelerate energy transition. The next decade is crucial for the success of energy transition and an accelerated deployment of PV, because any new investment in fossil power generation over this timespan will otherwise become a stranded asset later and increase the societal costs. Therefore, it is equally important that sustainable energy policy is taken into account. A 'sustainable-energy-policy-first' rule will be of most importance for avoiding stranded assets given the urgency for a fast energy transition induced by a fast progressing climate change. The most important sustainable energy components include PV, but also consist of wind energy, batteries, electric vehicles, heat pumps and green hydrogen-based synthesis routes for products. Sustainable energy elements shall receive priority to solutions in violation with ambitious sustainability criteria in general, and the European Green Deal in particular.

Effective public dialogue encompassing the total costs, risks and benefits, size of deployment (area matters) will ensure public support. The dialogue should run in the broadest sense within three dimensions:

» **Individual – household – community – regional – country - European level.** Each individual citizen should be involved in the dialogue, even in different roles as a representative of a household, member of an energy community, representative of regional government or a member state official. Effective public dialogue should be continuously assured by ETIP PV and PV related associations as one voice of Solar PV with member states and European Union as a whole.

» **Energy – ecology – economy costs.** The effective public dialogue for the high PV scenario should reveal actual benefits and current state-of-the-art costs of PV and their trends:

- PV is already competitive and can make a huge contribution in the next decade (2020-2030). This is key to remain in a pathway compatible with the Paris Agreement. This fact and such messages are missing in the public discussion. People still think that PV is an expensive technology, while the International Energy Agency mentioned in WEO2020 that solar PV is the lowest cost source of electricity mankind had access to in history. Media attention is addressed to the advantages that PV systems bring to society in the medium and long term but it is still too often focused on the high upfront investment costs of PV systems. Popular misconceptions of PV cost, energy production and environmental performance are long-lived and correcting these mistaken beliefs is difficult. Factsheets, conferences and webinars may increase visibility and raise awareness, but true engagement of citizens is needed for a big change. In the last several years, PV has not just reached generation costs compared to conventional electricity supply costs in practically all countries across Europe, but it has already exhibited significantly lower costs. Therefore, it is important that accurate information is conveyed to citizens as potential users and our society including decision makers more generally.

- A massive deployment of PV is already going on in the electricity sector and PV is a no-regret option in other energy sectors, whereas supporting technologies will further accelerate the demand for PV, in particular batteries and water electrolysers. We have to be aware that regulatory requirements and bottlenecks for the use of photovoltaics on a large scale already exist. So it is important to continuously identify these bottlenecks and facilitate their simplification to speed up the process.

- An energy system transition towards 100 % renewables leads to lower total system cost than other zero greenhouse gas emission options, and a major PV share is a fundamental driver for cost competitiveness.

- PV systems are more and more sustainable and can be recycled almost entirely, embedded CO_2 emissions can go down to zero as soon as sustainable input energy is used. Energy payback times continuously go down, while the energy return on energy invested steadily goes up, as a consequence of the energy learning rate.

- Attractiveness and local acceptance of new infrastructures and operations for the whole value chain will be affected by the costs.

» **Societal aspects with sustainable development goals and climate change contribution**

The Green Deal and the energy transition have serious consequences for the EU industrial sector. Coal and lignite mining is still a major economic activity in 12 EU Member states, but the phaseout of this activity as well as the use in thermal power plants is crucial to achieve the GHG reduction targets. Therefore, a socially acceptable employment alternative for approximately 240,000 citizens working in the sector is needed.

The retirement of coal power plants and the closure of mines should therefore be flanked with the accelerated deployment of PV. The construction of large scale PV plants in the coal regions over the next decade could generate about 225,000 construction jobs and the O&M sector could employ about 56,000 people in 2030. Nonetheless, even if the installation of solar photovoltaic electricity generation systems would provide new jobs, not everybody currently working in the mining sector will be able to transfer to one of these new jobs. To compensate, additional flanking measures for a just energy transition have to be put in place.

The realisation of the rooftop potential on existing and new buildings could create a significant number of local jobs and offer citizens the possibility to economically participate in the energy transition using and selling the locally generated electricity. Such a development would also have a positive impact for jobs related to battery storage and related sectors. Strong synergies with the transition in the transport sector with road vehicles can be expected.

The accelerated deployment of distributed as well as large scale PV plants will increase the annual PV market and raises the question of supply chain security. The ongoing COVID pandemic has shown the vulnerability of the supply chain, though the predicted growth of the European solar sector can revive the PV manufacturing industry and create permanent manufacturing jobs in Europe. [86]

(86) SolarPower EU Solar Jobs Report 2021

Recommendations

1. To support research programmes/project topics for S-E aspects of high PV/RES penetration

- **The role of (various) PV system technologies** in energy supply of a world with electrified sectors (sector coupling) throughout the diversity of Europe's regions.

- **Stakeholder potential analysis from urban and rural societies**: Europe is ahead of a huge increase of PV deployment, therefore social scientific research is needed for the identification of the existing and potential stakeholder which can help to boost the implementation: not the technical potential but societal potential (existing communities, regions under crisis/change, self-consumption campaigns to reduce fuel poverty, companies with decarbonisation strategies etc.) will be needed to reach European goals.

- **To work together with regulatory and administrative stakeholders for innovative regulatory and administrative approaches:** Collaborative research formats (such as sand boxes or living labs) between stakeholders (private/ commercial investors, installers, municipal/regional planning authorities, grid operators etc.) are needed to develop simplified designs of regulations with mitigation of bottlenecks, to identify factors increasing the attractiveness for implementation, and extract and disseminate findings on a European level.

- **Integrate and explore the role of PV for promoting behavioural changes contributing to achieve systemic changes.** PV is a technology that will play a key technological role in achieving great and complex challenges such those planned by the Green Deal or the strategic mission already defined by the EC "100 Climate-neutral Cities by 2030 – by and for the Citizens". Exploring how photovoltaic energy - decentralized, close to people and clean – is advisable as it can contribute to the promotion of holistic behavioural changes towards such big objectives.

2. Engage / Fund (all education levels):

To develop a more responsible approach towards a major integration among the European stakeholders and, between key actors and our society, for an efficient and effective deployment of photovoltaic energy.

- **Sand boxes for innovative regulatory and administrative approaches.** Collaborative research formats (such as sand boxes or living labs) between stakeholders (private/ commercial investors, installers, municipal/regional planning authorities, grid operators etc.) are needed to develop simplified designs of regulations with mitigation of bottlenecks, to identify factors increasing the attractiveness for implementation, and extract and disseminate findings on a European level.

- **Citizen science and Public engagement.** Citizens, Member States, Regions and Cities need to encourage a more responsible engagement looking for an active role of citizens, consumers, end-users, energy communities, etc... as a key piece/element in contributing to the sustainable energy transition (including PV expansion) and social acceptance. As commented in (1) this engagement and citizen science should go from direct collaborations with researchers to target some current research questions, to citizen science actions devoted, in example, to getting/acquiring data for better shaping the European energy policies and steering the transition. It is also urgent to consider and address European citizens' real needs, expectations and worries related to PV (2). Moreover, specific engagement for young generations, not only children but also those who start becoming independent and can make strategic decisions from scratch, should be promoted as change driving forces. In return to these engagements, it must be ensured that citizens acquire improved skills (lifelong learning) to act as ambassadors contributing to the expansion of PV technology in the energy transition.

- **Job creation and training**. The energy transition (including expansion of PV) will create new jobs and at the same time we need to take care for an alternative for the people working in fossil fuel sector. In order to get their social acceptance, they need to find new jobs if we replace fossil energy with PV otherwise they will be against the clean energy transition. Therefore, a very important topic is training and education and transferring skilled personnel from one industry/sector to another for both high level jobs but also for lower level jobs that do not require high level education. It is fundamental to gain overall social acceptance. This applies to the whole chain of PV and even more to the sectors that will be diminished or even abandoned. RES are not taken seriously into account by politicians, but due to union pressure, coal workers are taken into account. We know from analysis that RES can create much more jobs than coal and that there is almost no job generation in the oil and gas industry since it is highly automatized. The Spanish Government has decided to support coal regions to phase out from coal by funding transition to alternative economic activities. One option that is under discussion is creating auctions to install PV power plants in these areas.

  In the last decade, RES energy education programs have been implemented for university students, especially considering PV application from technical and economical point of views. Courses and training periods have also been launched for technicians and young people in technical institutes. Technical and, above all, practical preparation in this area is, in fact, decisive for facilitating young people's introduction into the world of work.

  The challenging goal for next years should consist in continuous learning approaches implemented in educational curricula involving pupils population since primary school. The idea is to implement educational programmes able to develop, in young generations, a mindset oriented towards the rational use of energy, the energy transition, the aware RES perception and the environment conscious respect.

  The goal is to make young people accustomed to the use of these technologies so that, as adults, they have an "intrinsic" propensity to adopt and use RES technical solutions. As digital natives are accustomed to using digital technologies, "RES" natives should have a strong propensity for these technologies and their applications.

- **Local energy initiative.** As a tool for citizens in the energy transition, which are funded by citizens, also enabling the participation of citizens in the energy transition. We need demonstration projects, how can we make cooperatives/make things work; which can be replicated. Living labs are a possibility for that also on different levels (target groups) → Smart Cities Initiative and European Bauhaus Initiative

- **Continuous funding/support of progress monitoring** (SET plan /ETIP PV / energy agencies)

KPIs for socio-economic aspects

KPIs

Possible KPIs that can be utilised for capturing progress in the socio-economic aspect fields are:

KPI	Target Value
Share of PV on total electricity generation / eRES generation in terms of capacity installed and electricity generation	By 2025: capable of offering a high share in MS countries of Europe By 2030: capable of offering a high share in all countries of Europe By 2050: capable of offering a high share worldwide
Job creation with PV	By 2025: capable of offering jobs in MS countries of Europe (i.e. 400,000 jobs in EU) By 2030: capable of offering jobs in all countries of Europe By 2050: capable of offering jobs worldwide
RES / PV cooperatives (state-of-the-art and future scenario(s)	By 2025: to be operational in MS countries of Europe By 2030: to be operational in all countries of Europe By 2050: to be operational worldwide
RES / PV crowdfunding platforms (state-of-the art and future scenario(s))	By 2025: to be operational in MS countries of Europe By 2030: to be operational in all countries of Europe By 2050: to be operational worldwide
RES / PV Energy Communities (state-of-the art and future scenario)	By 2025: to be operational in MS countries of Europe By 2030: to be operational in all countries of Europe By 2050: to be operational worldwide

Endnotes

i See Foreword in IEA PVPS Trends in Photovoltaic Applications 2020, Report IEA-PVPS T1-38:2020, IEA PVPS report- Trends in Photovoltaic Applications 2020 (iea-pvps.org): "Solar is the new king of the electricity markets," was one of the first key statements of the IEA Executive Director Fatih Birol when launching the most recent IEA World Energy Outlook in October 2020, acknowledging that solar PV electricity is becoming the cheapest source of new electricity in many countries around the world and will therefore continue to grow strongly over the decades to come.

ii Bogdanov et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy, 227, 120467 (2021), see https://doi.org/10.1016/j.energy.2021.120467

iii 100% Renewable Europe, How To Make Europe's Energy System Climate-Neutral Before 2050, see https://www.solarpowereurope.org/wp-content/uploads/2021/02/SolarPower-Europe-LUT_100-percent-Renewable-Europe-1.pdf.

iv ETIP PV Vision, see https://etip-pv.eu/about/our-vision/

v Global energy transformation: A roadmap to 2050 (IRENA, 2019), see https://www.irena.org/publications/2019/Apr/Global-energy-transformation-The-RE-maptransition-pathway.

vi Sky Scenario, see Sky scenario | Shell Global.

vii The Intergovernmental Panel on Climate Change (IPCC), states that the too slow decrease in global greenhouse gas (GHG) emissions will not allow to keep the average global temperature increase below 2 °C and as close as possible to 1.5 °C. According to this analysis, the global carbon budget will be used up very soon and a temperature increase of 1.5 °C would already be reached at the beginning of 2030, underlining that emissions need to be decreased drastically and fast.

viii SolarPower Europe, ETIP PV, ESMC, IPVF and VDMA

Multi-junction solar cell of III-V semiconductors and silicon, which converts 33.3 % of solar radiation into electricity. By comparison, the best conventional silicon solar cells to date achieve an efficiency value of 26.7 %. The higher power is enabled by fifteen very thin III-V semiconductor layers, which have a total thickness of only 0.002 mm. The entire solar cell is approx. 0.25 mm thin. The III-V layers convert the visible part of the solar spectrum particularly efficiently.

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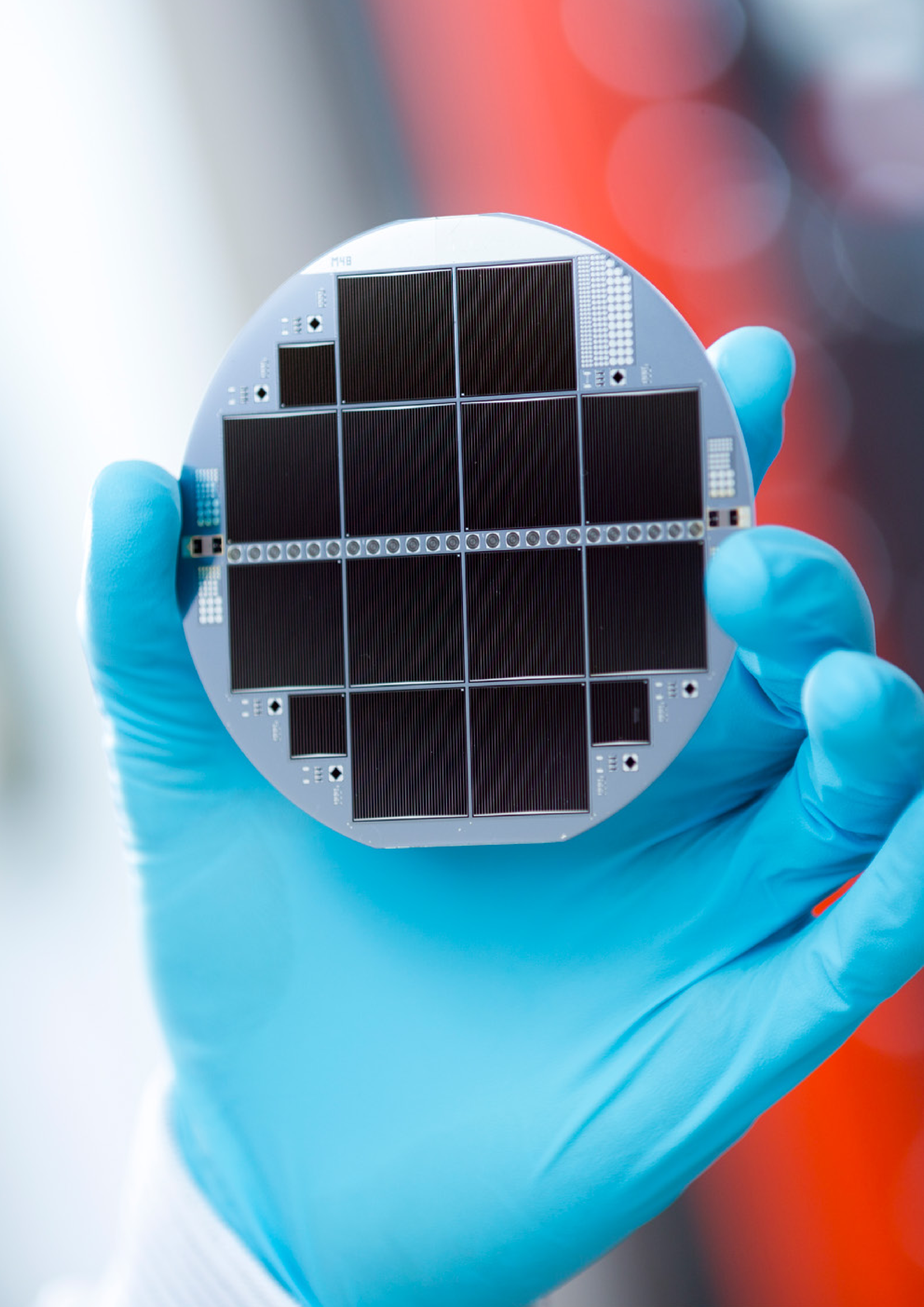
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