The European Technology and Innovation Platform for Photovoltaics

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Update

Strategic Research and Innovation Agenda on Photovoltaics

ETIP Photovoltaics

The European Technology and Innovation Platform for Photovoltaics

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1.
Introduction

This Strategic Research and Innovation Agenda (SRIA) is developed by ETIP PV, with the support of EERA Joint Programme on Photovoltaics, and provides an overview of the trends, priorities and pathways that PV technologies, science and applications are expected to follow in coming years. Photovoltaics (PV) has rapidly moved into the mainstream of the energy system thanks to innovation delivering rapid cost decreases and fast improvements in the performance and versatility of energy services. Solar PV energy production is at the heart of the European climate and energy policy as the European Union strives for climate neutrality by 2050 at the latest, notably with the implementation of the European Green Deal. PV is among the focal points of a European economy striving for resilience following the brutal disruption of the COVID19 pandemic and a notable beneficiary of the Recovery Plan for Europe. It also is a pillar of the renewed focus on energy security with European policies that accompany the REPowerEU in reaction to the invasion of Ukraine by Russia and the weaponisation of Russian gas exports.

Solar PV already stands as the most competitive energy source in Europe and beyond, with the IEA pointing in 2024 that 'More money is now going into solar PV than all other electricity generation technologies combined'[1]. PV installations are booming, with the EU installing nearly 1 GW of new solar PV capacity per week in 2024. The rapid pace of solar deployment is a direct result of the fast progress in innovation for solar PV technologies: at research level, research centres have been able to deliver a 0.6 percentage point efficiency increase per year since 2010[2]. Simultaneously, through innovation in labs and manufacturing process, PV systems have become much more material efficient contributing to a lower environmental impact and costs of production.

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.

[1] *https://www.iea.org/news/investment-in-clean-energy-this-year-is-set-to-be-twice-the-amount-going-to-fossil-fuels*

[2] *Ralf Preu, Fraunhofer ISE, 2023 ETIP PV Annual Conference*

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-use 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 focused on socio-economic aspects of the PV energy transition, bringing a transversal perspective to addressing the social, political and economic challenges and opportunities that may arise as PV moves into the mainstream (or even becomes the cornerstone of the energy system). 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.

Each challenge section includes specific objectives identified by the PV R&I community and industry stakeholders as crucial axes to address the structuring R&I challenges that the solar sector must solve to unleash its potential. Moreover, a number of roadmaps are listed to achieve each objective, each with a more granular focus that allows to explore R&I topics & priorities more finely.

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 2035.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.

2.
SRIA Overarching Challenges – Making the Energy Transition a European Success

2.1
Renewable electricity is the heart of the European energy system

Whether at global or European scale, electricity is the cornerstone of decarbonised 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 & socially sustainable way. A massive rollout, integration into the energy system and our living environment, and the circularity of the entire value chain are needed to successfully lead the energy transition.

The potential and forecast of solar photovoltaic development have been studied in several scenarios and visions. Although 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. Overall, PV deployment rates have consistently exceeded predictions from both institutional and research modelling, and photovoltaics are expected to represent 325 GW of installed capacity at the end of 2024 in Europe, a more than 50% increase in the span of 3 years. Solar energy is on track to become a major supplier of our carbon-free electricity, already delivering 10% of Europe's electricity in 2023[3]. This trend is for instance 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]

The European Union has adopted a wide panel of policies to accelerate the uptake of photovoltaics and other renewable energy sources, notably achieving objectives related to climate change mitigation and keeping the rise of global temperature below 1.5°C as per the 2015 Paris Agreement. These policies for instance include different iterations of the Renewable Energy Directive, most recently introducing a 42.5% target for renewables in final energy demand by 2030, and the adoption of the European Green Deal. On 21 April 2021, the 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.[4]

Following the COVID 19 disruptions and later the invasion of Ukraine and the ensuing energy price crisis in Europe, solar PV also emerged as a pillar of energy security and resilience for the European economy, helping to keep electricity prices affordable for European households and industry, and representing a rapidly scalable alternative to fossil energy sources and their accompanying geopolitical vulnerability. The REPower EU package introduced a European Solar Strategy to bolster the Union's energy security through the deployment of 750 GWdc of PV capacity in Europe by 2030 and the consolidation of European PV manufacturing with a target for an integrated value chain representing 30 GW of annual production capacity.

3 *IEA PVPS, Snapshot of Global PV market 2024*
4 *https://www.consilium.europa.eu/en/press/press-releases/2021/05/05/european-climate-law-council-and-parliament-reach-provisional-agreement/*

2.2
Massive rollout and integration of solar energy at affordable cost, in an environmentally & societally sustainable way

Solar PV is growing at a fast pace throughout the world, with 447 GW of new PV capacity deployed in 2023. Its current contribution to global electricity demand is around 8% and is rapidly growing[5]. Its contribution to electricity demand in the EU is around 10% on average in 2024, and it is already considerably higher in several EU member states: e.g. over 20% in Spain and the Netherlands, 14% in Germany, around 18% in Greece, and nearly 12% in Poland and Belgium[6].

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

- Further reduce solar PV generation costs. Reductions here offset energy system costs linked to the increasing role of storage technologies such as batteries.
- Enable the deployment of PV solutions adapted to a wide range of applications. PV systems increasingly comprise integrated multipurpose applications. They include solar electricity-generating buildings, car roofs, and many other surfaces. Other rapidly emerging market segments of such integrated PV solutions include PV systems integrated into infrastructure (roads, noise barriers, dikes, etc.), PV in combination with agriculture (Agri-PV) which often also delivers land or water management, biodiversity or other environmental services.
- Guarantee the reliability of PV systems and enable the development of a circularity value chain for photovoltaics.
- Integrate massive amounts of photovoltaics into the European grid and broader electricity system, to deliver affordable, reliable and renewable electricity, notably thanks to enabling digital solutions.

[5] *https://ember-climate.org/topics/solar/*
[6] *IEA PVPS, Snapshot of Global PV Markets 2024, https://iea-pvps.org/wp-content/uploads/2024/04/Snapshot-of-Global-PV-Markets_20241.pdf*

2.3
Supporting Economic Recovery and Building the Value Chains for Renewables

2.3.1
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 landscape is changing rapidly with a growing focus on bolstering supply chain resilience by increasing PV manufacturing capacities in various parts of the world, including Europe. This is notably illustrated by the European adoption of the Net Zero Industry Act which introduces a 40% target for European manufacturing of clean energy technologies, and the organisation of a European Solar Photovoltaics Industry Alliance.

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 the 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 breakthrough concepts in technology, manufacturing and applications, it is essential to develop an industry hand in hand with a research & innovation strategy to ensure Europe's strong position in this sector. The announcement of a Co-Programmed Partnership on solar Photovoltaics in 2024 is a key milestone in adapting the European R&I environment for PV innovation towards a stronger integration with the industrial sector and enabling innovation to accompany the scale up of the European PV industry on the supply as well as the demand side.

2.3.2
European industry success in the global competition relies upon high market ambitions, rapid innovation and a future-ready sustainable value chain

The PV market as of 2024 is defined by a trend towards consolidation of supply, led notably by excessive production capacity globally, which has grown even faster than PV demand. This situation creates a challenging environment for reinforcement of the European PV manufacturing sector, notably as OPEX factors hamper the competitiveness of these actors compared to the global competition which benefits from either large-scale industry and integrated value chains or significant public support on OPEX. In most segments of the silicon-based PV value chain, economies of scale are critical. For Europe, a threshold for competitiveness has been identified when the integrated value chain (from polysilicon metal to modules) exceeds annual production volume between 5 and 10 GW, including major "Giga factories" with several GW of production capacity for various segments of the value chain. Several projects have been announced since 2022 which are aiming to achieve the European Solar Strategy of 30GW of integrated manufacturing capacity in Europe by 2030, however, investments are often struggling to materialise in a landscape of oversupply and low opportunities for margins linked to OPEX costs often exceeding modules sales prices.

For Europe, beyond the scale up of a "best in class" industry, the region's strong position on research and development provides perspective for enabling long term competitiveness in a sector with short technology cycles and rapidly evolving technologies, solutions and manufacturing processes. Novel approaches, including ultra-fast roll-to-roll manufacturing of next-generation PV technologies such as perovskites, represent an opportunity in the short to medium term. These technologies enable a range of new, integrated applications, which are vital for large-scale deployment in a societally and environmentally sustainable way.

2.3.3
Utilising Circularity to Ensure a Sustainable Transition

The European Union plays a leading role, as a key global demand market, in defining requirements for PV technologies, and policies such as the Critical Raw Material Act have a strong impact in fostering the inclusion of circular components or recycled materials in PV modules available to the European market, representing a potential opportunity for the European industry, as other regions are not yet focusing on this crucial topic.

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).[7] As a circular economy covers the entire lifecycle of a product, it requires a broad and systemic approach to production.

2.3.4
The role of the ETIP PV SRIA in accelerating the R&I process for solar PV

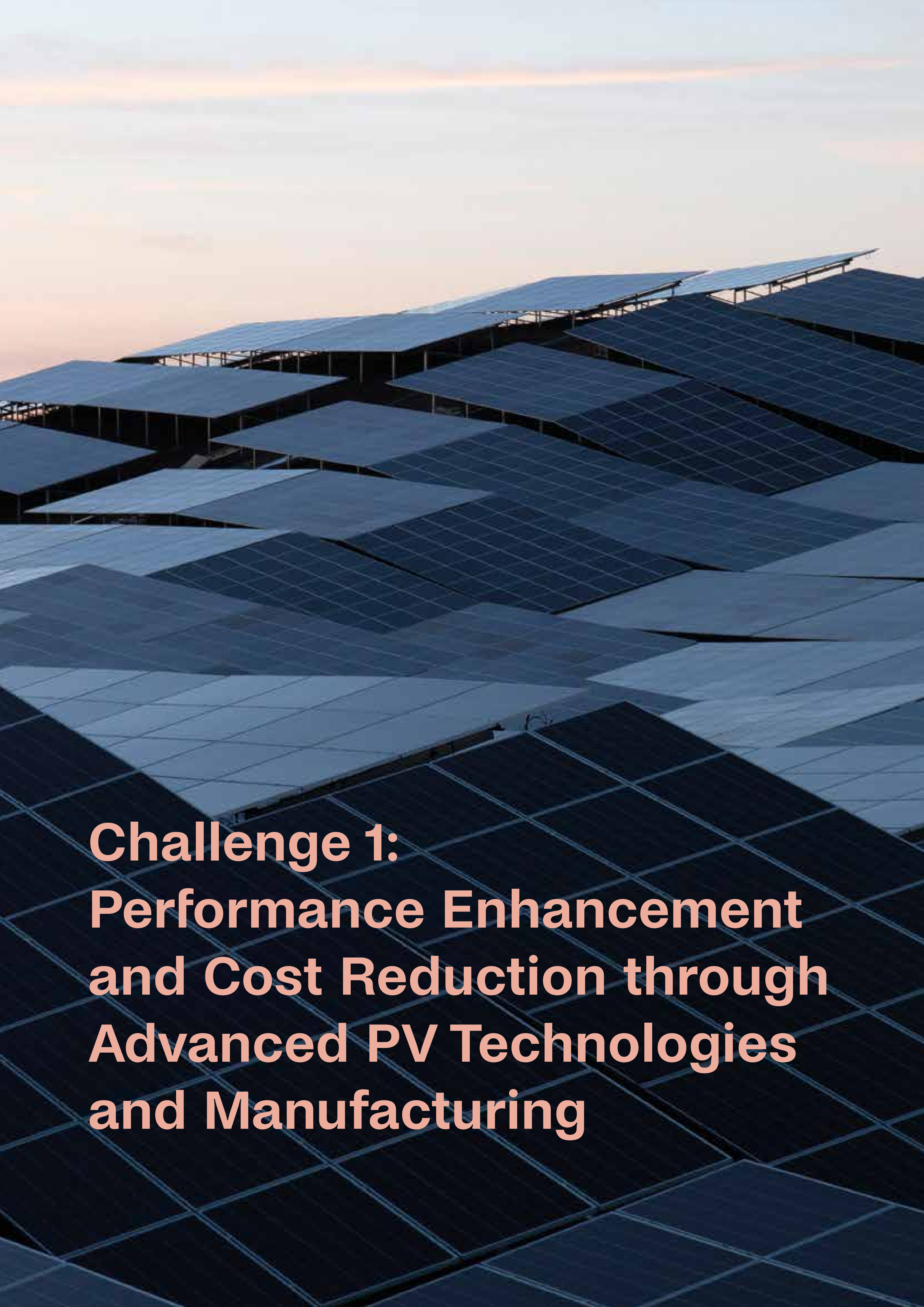
The ETIP PV Strategic Research and Innovation Agenda aims to provide a strategic pathway to accompany the progress of the PV R&I in enabling the implementation of the objectives of the Renewable Energy Directive, European Green Deal, the RePowerEU initiative and the European Solar Energy Strategy:

- Enable the European industry to foster the green and digital transitions and at the same time defend its open strategic autonomy, preserve its competitiveness on the global market, maintain a high level of employment and quality jobs in Europe and strengthen its ability to innovate and produce in Europe.
- Contribute to the overall Horizon Europe 35% Climate Action expenditure target, the European Green Deal and the REPowerEU.
- Contribute to the objectives of the Critical Raw Materials Act and the Net-Zero Industry Act of the Green Deal Industrial Plan.
- Support the R&I pillar of the "EU Solar PV Industry Alliance" and consequently facilitate the build-up of a large-scale PV manufacturing capacity in Europe.

In terms of broader technological focus across Technology Readiness Levels for PV R&I, the SRIA covers:

- Next generation PV cells & module technologies (e.g. crystalline Si-tech, thin-film, perovskites etc.) across the whole value chain.
- Emerging innovative PV deployment applications (e.g. agri-PV, building-integrated PV, floating PV) for an optimal use of renewable energy potential in synergy with other economic sectors' needs and biodiversity.
- Integration of PV in flexible energy generation systems.
- Circularity by design, recycling, maintenance & end-of-life management of PV systems and key raw materials of the PV value chain.
- Enabling technologies and tools for demonstrating and scaling up of next generation PV.

[7] *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 queen of electricity markets by IEA Executive Director, Fatih Birol [IEA (2023), World Energy Outlook 2023, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2023] 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 focus of this challenge is to outline research & innovation needs for performance enhancement covering all components of a PV system including their production through advanced manufacturing technologies.

The momentary energy output of PV modules is defined by the efficiency (Wp/m^2), whereas energy production over a certain period is described by the energy yield (MWh/MW/year). Through improvements in manufacturing processes, gains in material use, and - crucially – improvement in PV efficiency, PV modules costs have undergone a consistent cost reduction with a learning rate of 36% in the 2010-2020 period. As PV modules become increasingly cheaper, other components of the PV system - Balance-of-System (BOS) – are representing an increasingly significant share of the overall cost of a system, and these become a more important factor in cost reduction. 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 the lifetime 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 per kWh

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. They also include the various applications needed to make PV a cornerstone of the future energy system.

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

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3.1 Objective 1: PV modules with higher efficiencies, long lifetime, and lower costs

This objective focuses on improving PV module efficiency, reliability and reducing costs of PV electricity. It covers the various PV technologies that have already reached industrial maturity level as well as others that are on the cusp of industrialisation or are still at the R&D stage. 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, especially of PV modules and of many BOS-components, scale with area (cost of land, materials, transport...). Thus, increasing the energy output in Wp/m2 or ultimately kWh/m2 through higher efficiencies is a very strong leverage for reducing LCOE.

ii. Increasing electrification of the energy system in sectors like heating and cooling, transport and chemical conversion requiring a massive expansion of electricity generation in Europe. In urban environments, local electricity generation and storage can reduce transmission costs substantially but **space** on buildings, vehicles, infrastructure etc. needs to be used as effectively as possible.

iii. In a multi-TW PV industry other **resource constraints** begin to emerge, ranging from greater challenges to source specific raw materials to available production capacities. Again, higher efficiencies – but also the emergence of alternative technologies that valorise different materials – can help to alleviate these constraints.

There are many photovoltaic technologies that stand at various levels of technological and, more crucially, industrial maturity. In the perspective of a strategic approach to research and innovation efforts and a stronger integration between research and innovation and industry in order to shorten the lab to market pipeline in the European PV sector, it is crucial to have a differentiated approach towards strategic innovation that have an industrial application in the short to medium term.

Below are the technology roadmaps for PV technologies identified as high priority areas in this perspective.

3.1.1 Roadmap 1: Silicon PV Modules

Rationale for support

Although the available capacity for manufacturing of wafer-based silicon solar cells and modules remains low in Europe and the industry is dominated by China, Europe remains a strong actor in the more advanced technology concepts, both related to 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 a leading position in silicon photovoltaics, especially as silicon PV will be the first choice for the bottom technology in tandem PV cells and modules.

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

- Achieving an integrated 30 GWp manufacturing capacity along the entire value chain (poly-Si to PV modules) with low carbon footprint and circularity in Europe (in line with current European objectives)
- Further lowering the LCoE of both utility-scale PV, rooftop and Integrated PV
- Reinforcing Europe's position in silicon PV technology regarding high performance and lower costs, while at the same time embedding sustainability and circularity (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 more than 95% 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 have resulted in very low LCoE of 10 €/MWh (Middle East) to 50 (Germany) €/MWh.

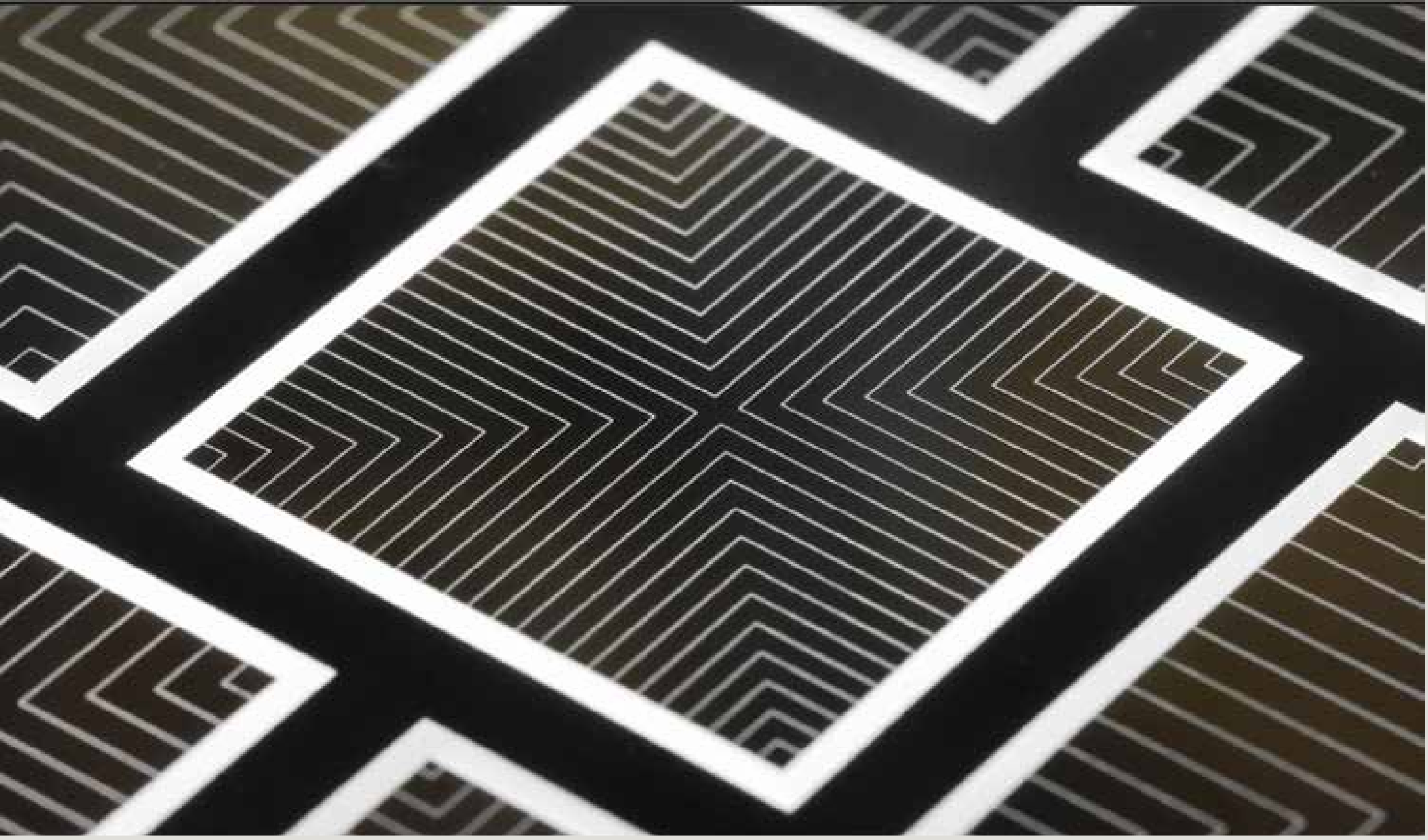
Targets, Type of Activity and TRL

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 allows efficiencies of over 30% in hybrid tandem structures, and of over 40% for multi-junction devices (see Roadmap 4).

Until 2035 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 high-performance silicon films including band engineering enabling high conversion efficiencies.
    - Kerf-free processes to minimise material wastage, leading to higher material utilisation efficiency and reduced production costs.
- Development Research Actions (TRL3-5)
    - Efficient processes for low-cost 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) content, 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.
    - Process and equipment development for epitaxial and alternative kerf-free wafers
    - 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.
- Flagship Actions (TRL7-8)
    - Further development and supporting processes for diamond-wire cutting of 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 wafers and therefore a narrow efficiency distribution after cell processing.



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

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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 µm) 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. (poly-Si alloyed with C or O; dopant-free transparent passivating contacts, amorphous/nanocrystalline-Si alloyed with C or O; material research, opto-electronic properties); including thin and ultrathin solar cells, and enabling >26% cell efficiency for G12 wafers; optimization of transport layers and carrier extraction in advanced solar cells
- Knowledge development of degradation mechanisms in modules during heavy stress conditions and mitigation procedures.
- Development of low stress metallization and interconnection technologies for thin and 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, 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.
  - 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
- Improvement in high-performance cell concepts (for example heterojunction cells beyond c-Si/a-Si), and on the generation, transport and extraction properties of the same.

- 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 (poly-Si or silicon heterojunctions with doped amorphous silicon electron and hole contacts and have >26% cell efficiency for different cell designs (front and back contacted and back-contacted)
  - 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 while maintaining long lifetime.

- 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.

3.1.2 Roadmap 2: Perovskite PV modules

Rationale for support

Perovskite-PV has been identified as the most promising emerging PV technology which also includes multi-junction approaches; with leading companies and R&D in Europe and around the world (see Roadmap 4).

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

- abundance of materials
- low material and energy usage
- potential low-cost and high-speed production methods[8]
- Suitability to be combined with other mature technologies, such as Si or CIGS, in a multi-junction solar cell.

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 cells. 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 a highly versatile PV technology. Pk-Si tandem solar cells are reaching new heights and surpassing all Si-based solar cells' efficiency thresholds.

Perovskites PV solutions have proven their tremendous potential for reaching high efficiency of cells, as industrialization of this solution progresses, a major R&I challenge lies in solving remaining challenges linked to the stability and reliability of perovskite cells.

Status

Industrial activity

The industrial development of Pk-PV is currently progressing rapidly in Europe and worldwide. With respect to single-junction perovskite solar cells (tandem activity detailed in roadmap 7), many companies ranging from startups to large PV manufacturers are investing in R&I to bring this technology to market[9], with solutions explored ranging from flexible Pk-PV made by ink jet printing, with sheet-to-sheet processes, to opaque Pk-PV on glass for modules more similar to existing silicon products. A major milestone in the recent years is the rapid entry of nearly all major PV manufacturing companies into perovskite R&I,with a strong focus on Pk-Si tandems, but also with the announcement of large scale production lines following notable milestones such as MW scale perovskite demonstration plants in 2023[10] by GCL[11], following the commissioning of a 100 MW pilot line for perovskite production.

Efficiency and scalability

Pk-PV's power conversion efficiency in a single-junction architecture has increased from 3.8% at its discovery in 2009 to 26.2% in 2023[12]. With that, single junction Pk-PV has joined three more mature PV technologies (cSi, GaAs and GaInP) in reaching at least 75% of their Shockley-Queisser performance limits.

Scalable processes have been implemented for various deposition methods used in the production of the perovskite absorber layer as well as for the other layers forming the Pk-PV.[13] These scalable fabrication technologies include solution processes[14], physical depositions[15], and hybrid approaches that combine both methods in a sequential procedure[16]. Successful demonstrators have been produced by applying single step wet deposition by coating or printing the perovskite precursors, followed by a quenching step (either solvent, gas, vacuum, thermal quenching or a combination of them). Single-step precursor co-evaporation has also yielded highly efficient perovskite absorber layers with record efficiency of 26.21% on 0.1 cm^2 and 24.88% on 1 cm^2 [17]. Hybrid depositions thermal+solution resulted in 24.3% efficiency[18], with possible applications focusing on tandem cells. The opposite hybrid process solution+thermal has also been considered for improving the crystalline quality of the perovskite film, reaching efficiency above 25%[19].

Stability

Stability remains a challenge for Pk-PV despite continued improvement.[20] It is one of the leading challenges to be solved to guarantee the market scalability of this technology. 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 and IEC 61646). At the same time, field tests of perovskite modules and panels have been reported[21] and both research labs and industry are more and more focussing on outdoor characterisations and multi-year field tests. Nevertheless, cell module and panel stability and reliability need to be investigated, as a major factor taken into account in solar cell deployment.

[10] *https://www.pv-magazine.com/2024/06/20/gcl-says-perovskite-solar-module-passes-silicon-degradation-tests/*
[12] *https://www.nrel.gov/pv/module-efficiency.html*
[13] *Park & Zhu, Nature Reviews Materials 2020, 5, 333–350 (https://doi.org/10.1038/s41578-019-0176-2); A. Agresti et al. Nano Energy Volume 122, April 2024, 109317 (https://doi.org/10.1016/j.nanoen.2024.109317)*
[14] *Z. Saki et al. Energy Environ. Sci., 2021,14, 5690-5722 (https://doi.org/10.1039/D1EE02018H)*
[15] *Hwang, Jae-Keun et al. Energies 2023, 16, 5977 (https://doi.org/10.3390/en16165977)*
[16] *Felix Utama Kosasih et al. Joule 2022, 6, 2692-2734*
[17] *Junjie Zhou et al. Joule 2024 https://doi.org/10.1016/j.joule.2024.02.019*
[18] *Tan, L., et al., Combined Vacuum Evaporation and Solution Process for High-Efficiency Large-Area Perovskite Solar Cells with Exceptional Reproducibility, Adv. Mater., 35, 2205027*
[19] *Z. Shen et al. Energy Environ. Sci., 2022, 15, 1078-1085 (https://doi.org/10.1039/D1EE02897A)*
[20] *Khenkin et al. Nature Energy 2020, 5, 35–49 (https://doi.org/10.1038/s41560-019-0529-5); Parvesh K. Deendyal et al. Solar RRL 2024, 8, 2300957 (https://doi.org/10.1002/solr.202300957).*
[21] *Sara Pescetelli et al. Nature Energy 2022, 7, 597*

Toxicity: lead and toxic solvents

Ensuring the safety of perovskite devices manufacturing and operation is a key condition of the successful market uptake of this technology.

The most-commonly used DMF[22] solvent need to be substituted with greener alternatives in the production prcess. Dimethyl sulfoxide (DMSO) and acetonitrile (ACN) are relevant options, as they have enabled efficiencies > 21% to be achieved. However, questions remain to answer in solvent and material solutions to ensure the stability of the define, notably at a large scale. Vapour-based deposition techniques are emerging as a solution to solve this issue.

Lead is often use to produce perovskites, however it poses a toxicity problem and is extensively regulated. Challenges related to lead can be tackled either via Pb substitution of Pb capture. In the short term however, Pb-free perovskite solar cells are currently limited in their efficiency and stability, therefore all prominent industrial endeavors focus on Pb-based solar cells. The toxicity challenge related to lead should however be nuanced, as Pb amount in the modules is not larger than $1g/m^2$ and numerous studies have shown that even in the worst-case scenarios where the encapsulation of the modules would be completely damaged and all of the Pb content would leak out of the module and into the environment, the Pb contamination level would still be below allowed thresholds for health, safety and environmental impacts.

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, while commercial products are expected to achieve technical lifetime consistent with the economics of a PV project. Depending on the learning curve, Pk-PV module manufacturing could quickly achieve comparable costs compared to currently commercial technologies.[23]

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, charge transport, interface impact and ions/defect contribution on atomic level. This will help to further improve efficiency, intrinsic lifetime and material usage.
- Lead-free Pk-PV or lead-free highly efficient perovskite inspired cells
- Pk-PV with features to immobilize lead in case of catastrophic events.
- Utilize low-cost, high performing and fast processable transparent electrodes and charge transporting layers for perovskite PV through novel materials/processes
- Understand, model and resolve stability issues of perovskite absorber/solar cells.
- Develop recycling strategies for early stages of new (thin film) PV technology
- Integrate near-UV absorbing perovskites with and Near-IR absorbers for PV windows with transparency in the visible light range
- Evaluate the effect of green solvent systems for perovskite formation.
- Investigate the correlation between the perovskite architecture and cell durability in variable integration processes.
- Utilizing Material/Device Acceleration Platform (MaDAP[24]) integrated with AI in a closed loop topology to explore the parameter space and to optimize the solar cell.
- Utilizing simulation or AI for novel material research and development.
- Develop encapsulation methods introducing simplified processing of thin and light-weight cells

[22] *dimethylformamide*
[23] *L.A. Zafosching et al., IEEE Journal of Photovoltaics 10(6) (2020)*
[24] *J Zhang et al. Accounts of Chemical Research (2024) (DOI: 10.1021/acs.accounts.4c00095)*

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.
- Replace high-cost organic semiconductors materials with abundant and low-cost metal oxide (or oxysulfide) equivalent.
- Explore processes for production in ambient atmosphere.
- Development of suitable lamination and/or encapsulation materials for panel production.

Demonstration Actions (TRL 5-7)

- Demonstrate at pilot level highly efficient and 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 and stable 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
- Field test of perovskite modules and panels and comparison with accelerated life time tests.

Flagship Actions (TRL 7-8)

- Develop next generation production equipment for larger size modules, very high yield and throughput, automated manufacturing and low energy and material consumption to leverage economies of scale and improve the environmental footprint for perovskite module production.
- European pilot line 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. Facility will be accessible from external user based on a typical Infrastructure Policy.
- 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 GWp production capabilities with one single roll-to-roll production line. Facility will be accessible from external user based on a typical Infrastructure Policy.

Several PV technologies, at varying technology readiness level, have a more unclear path to market in the short to medium term, although they do still represent a significant untapped potential in a longer-term perspective. As such, consistent R&I efforts – if not necessarily as comprehensive as in other segment of PV R&I – to identify pathway towards industrialisation of such technologies are relevant in the perspective of a strategic approach to the industrialisation of PV innovation.

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

Rationale for support

Various thin-film PV technologies are aiming to achieve high efficiency and long lifetime at competitive production costs to deliver competitive solutions and versatile applications.

Status

Mature Inorganic thin film PV Technologies

CIGS and CdTe are mature and commercially available thin film technologies which show lab cell record efficiencies of 23.6%[28] and 22.6%[29], respectively, and mini module efficiencies surpassing 20%. Current commercial CIGS and CdTe modules have aperture efficiencies in the range of 13-15% and 18-19%[26,27] respectively and existing production lines also show already today a relatively low carbon footprint per Wp on a module level.

The annual CdTe production stands at 12.1 GWp (2023) while the annual production of CIGS was approximately 1.8 GWp in 2022[30] giving these technologies a market share of 4% in 2022[31].

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. Moreover, these technologies make use ofuse comparatively rare elements, regarded as critical raw materials by the European Union.[32]

In a concentrated market with a limited number of players (e.g. only one manufacturer producing CdTe PV modules), European R&D landscape on various thin films technologies remains robust, and there has been a successful track record in bringing technologies from lab to market from institute that continue working on these technologies despite a growing focus on perovskites.

28 https://www.nature.com/articles/s41560-024-01472-3
29 First Solar module Datasheet, 2023; National Renewable Energy Laboratory 2024 (available at: www.nrel.gov/pv/cell-efficiency.html)
30 Photovoltaics Report, Fraunhofer ISE 2023
31 Fraunhofer ISE: Photovoltaics Report, updated: April 2024
32 https://ec.europa.eu/docsroom/documents/42849

Organic PV technology

The technology of Organic Photovoltaics (OPV) has recently achieved the record cell efficiency of 19.7% (on 0.06 cm^2) paved by a staggering 50% rise in efficiency in the last five years. [33]

The record efficiency for OPV mini-modules currently stands at 15.7% (on 19.3 cm2), and the typical efficiency of final products is 5–7%.[34] 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 €/Wp.[35,36] Significant R&I challenges remain towards the industrialisation of OPV despite a promising for low cost production.[37]

Emerging thin-film technologies

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, $ZnSnP_2$, ZnSnN2, (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 alternate technological solutions:

Record efficiencies:

Cu2ZnSn(S,Se)4 (CZTSSe)	13.8% [38]
Sb2(S,Se)3	10.7% [42]
CuO2	8.1% [43]
Zn3P2	6.0%

Targets, Type of Activity and TRL

Like Si-PV or Pk-PV single-junction cells and modules, all thin-film PV technologies are expected to reach efficiency levels be comparable to current existing PV technologies (module efficiency threshold of 20+%) within 5 years. At the same time, thin-film PV module manufacturing should quickly achieve comparable or lower costs compared to current commercial technologies.[39]

[33] *K. Kiu et. al. 19.7% efficiency binary organic solar cells achieved by selective core fluorination of nonfullerene electron acceptors, Joule 8, 835-851 (2024).*
Green, M. et al. Solar cell efficiency tables (version 57). Progress in Photovoltaics 29, 3 (2021)

[34] *Green, M. et al. Solar cell efficiency tables (version 63). Progress in Photovoltaics 32, 1 (2023)*

[35] *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)*

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

[37] *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)*

[38] *J Zhou et. al. Control of the phase evolution of kesteriteby tuning of the selenium partial pressure for solar cells with 13.8%certified efficiency. Nature Energy 8, 526-535 (2023)*

[39] *L.A. Zafosching et al., IEEE Journal of Photovoltaics 10(6) (2020)*

Mature thin-film Technologies

For CdTe and CIGS, the main challenge lies in scaling up production capacity at a competitive cost to profit from the scale 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 area modules (threshold of 15%) and further increasing long-term stability. Additionally, IR absorbing or UV and IR absorbing (i.e., transparent) OPV can find applications on windows. Since OPV will initially mainly serve (transparent, indoor, etc.) niche markets, the stability criterion is less severe than for standard outdoor modules. An efficiency over 10% can be achieved with an average visible transmission of ~50%.

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 18% (module) and be able to provide a competitiveness factor compared to available 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. In this case the use of Materials/Device acceleration platforms (MaDAPs) that integrate robotic device fabrication and characterization with AI-driven data analysis and experimental design, permits the accelerated optimisation of material combination and device layout that permit to reach the targeted efficiencies.

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 low temperature processed selective contacts in CIGS solar cell structures. Improving the efficiency and thermal stability of CIGS low band gap devices for applications in monolithic tandem devices
- Increasing efficiency for high band gap CIGS absorbers as future top cell materials for 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
- Utilizing Material/Device Acceleration Platform (MaDAP) integrated with AI in a closed loop topology to explore the parameter space and to optimize the solar cell.

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.
- Utilizing Material/Device Acceleration Platform (MaDAP) integrated with AI in a closed loop topology to explore the parameter space and to optimize the solar cell.
- 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 the 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
- Developing CIGS as bottom cell material for tandem devices
- Stability and degradation models

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
- IR absorbing OPV with high average visible transmittance
- 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
- Develop encapsulation methods introducing simplified processing of thin and light-weight cells for tailored integration.
- Develop of tandem cells with organic subcells such as Perovskite/OPV opaque and semi-transparent applications (for BIPV, VIPV, Agrivoltaics etc.)

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

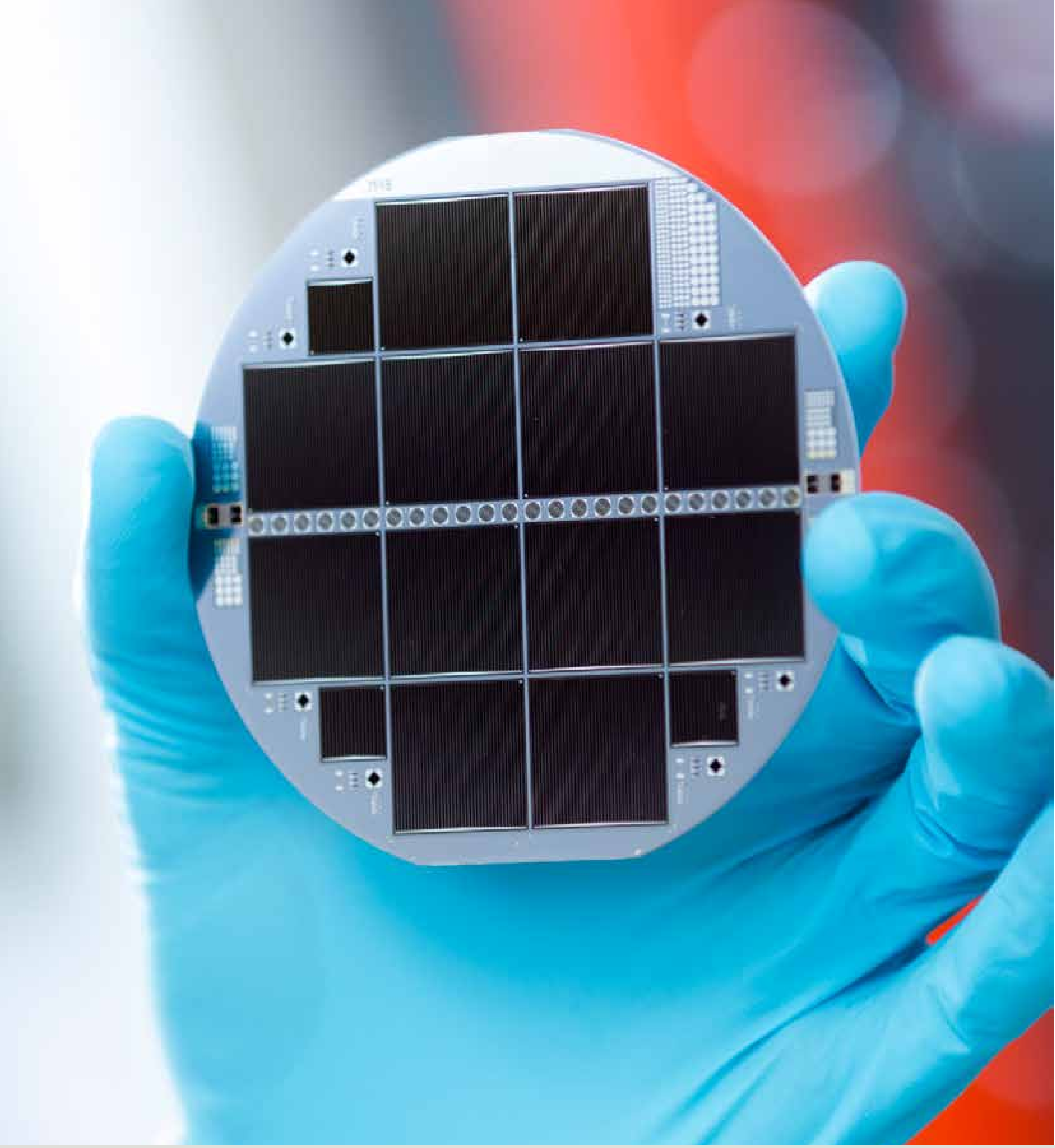
- Realisation of in-line characterisation for process control utilizing digitalisation, machine learning tools and IoT concepts.
- Mass customized BIPV elements with various colours, transparencies and sizes fully compatible with classic facade elements
- Stability and degradation models

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)

- 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)



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.

The longer-wavelength radiation penetrates the III-V layers and is absorbed in the silicon. The new cell is based on the dominating silicon solar cell technology, which commands more than 90 % of the global market. In fact, the two types of solar cell can hardly be distinguished from each other on the basis of outward appearance. At the same time, this new approach allows efficiency values to be reached which would be physically impossible with a simple silicon solar cell.

KPI for PV technologhies with higher strategic industrial priority

technologies		KPIs for multi-TW deployment (2035)										other KPIs for lower maturity or different applications				
		EU manufacturing capacity				performance & reliability sustainability & circularity (aligned with challenge 2)				supply chain & materials (in agreement with Critical Raw Materials Act)		towards manufacturing & market needs		performance & reliability sustainability (aligned with challenge 2)		supply chain & materials (in agreement with Critical Raw Materials Act)
Architecture	materials	EU total production (GW) by 2035	% of EU materials in value chain (BOM & equipment)	pilot production (MW)	bottleneck	module efficiency (%)	LCOE (in medium irradiance level 1300kWh/m2a) Utility (€/MWh)	reliability (years)	Bottlenecks	CRM reduction/ Suppression	Bottlenecks	application	Bottlenecks	cell / module R&D efficiency (%) TRL5 / (size)	reliability (years)	CRM reduction/ suppression
single Junction	crystalline Silicon	30 (from materials to modules, and value chain)	>45%	10-100 (of advanced concepts/ equipment)	EU equipment competitivness (€, tput, uptime, opex, thin wafers)/ silicon puller- DWSawing/ ingot/ manufacturing missing in EU	>25,5	25	40	stability, proof of bankability, Usage/ recycling of CRM, slow regulation framework and industrial policy;	In, Si, Ag, Bi	CRM free	develop Si based technology for new markets: spatial, low weight...	cost-efficient production processes, equipment, efficiency, reliability	>27 / G12	50	no CRM
single junction	perovskite	N/A	>45%	10-100 (of the whole value chain)	throughput, large scale deposition, equipment , reproducibility	>23	< single junction Si	25 (demonstrated by accelerated indoor testing)	stability, lead management, toxicity of solvents, outdoor performance validated, lack of standards for ageing testing, expensive organic materials, new encapsulants	In	value chain for PK cells, material supply availability for TW scale?	develop the market for PK based modules (iPV, climate?)	stability, lack of outdoor data, standards	27/ 30*30 cm	25	no CRM, supply availability? Lead issues?
single junction	CIGS	N/A	>45%	N/A	In, reproductibility , lack of EU manufacturers (only 1)	20	< single junction Si	25	upscaling with low cost and high efficiency	In, Ag	value chain for CIGS cells, material (In) supply availability for TW scale?	develop the market for CIGS based modules (iPV, climate?), high-bandgap CIGS for tandem applications		N/A	N/A	no CRM
tandem	perovskite on silicon	1GW?	>45%	100-500 (of the whole value chain)	throughput, large scale deposition	>27	<25	30 then 50 (demonstrated by accelerated indoor testing)	stability, upscaling of absorber and charge-transport laers, scribing, lead management, outdoor performance validation, lack of standards, encapsualtion	In, Si, Ag, Bi	value chain for PK cells, material supply availability for TW scale?	same as Silicon based modules	stability, lack of outdoor data, standards, stability	35 / G12	50	no CRM Lead issues?

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.

3.1.4 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. Tandem perovskite have rapidly progressed towards the appearance of commercial product, notably with the launch in 2024 by European manufacturer Oxford PV of a 26.9% efficiency perovskite/silicon tandem[25]. Investments from most major global PV manufacturers are underway to develop tandem perovskite solutions and bring products to market in the coming 5 years Pk-Si tandems represent the largest segment of tandem technologies investment in 2024, having demonstrated robust efficiency and stability performance.

Status

Silicon based tandem solar cells, especially perovskite-silicon tandem devices promise considerably lower costs and scalability, having achieved 33.9% efficiency at lab scale.[26] In Europe, the industrial focus is on perovskite-based tandem PV, either in a monolithic (2-terminal 2T) or 4-terminal (4T) configuration. Oxford PV (Germany and UK) is specializing in 2T Si-perovskite tandem solar cells and together with Fraunhofer ISE, they have announced a 26.9%-efficient full-sized tandem module (1.68m2) for commercialisation.

Enel/3Sun (Italy), Meyer Burger (Germany and Switzerland) and Q-Cells (Germany and Korea) are also developing 2T Si-perovskite tandem solar cells. Voltec, Solertix, Evolar/FirstSolar are focusing on semi-transparent perovskite on glass as an upgrade for existing PV modules like c-Si or CIGS with the 4-terminal approach, where the PV

25 *https://www.oxfordpv.com/news/oxford-pv-debuts-residential-solar-module-record-setting-269-efficiency*

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

module's front sheet can be replaced by a glass containing the semi-transparent Pk-PV module.

In China, LONGi is currently the most prominent Chine company that aims at industrializing 2T Si-perovskite tandems having achieved a series of PCE record of 33.9% on 1cm^2-sized solar cells, and a PCE record of 30.1% for a M6 commercial size cell in June 2024[27]. 4T Si-perovskite tandems are being developed by Microquanta Semiconductor (PCE = 21.4% with PERC and tandem area of 20cm^2), but they seem to focus more on rigid single-junction Pk-PV as they are already producing 60×120 cm^2 panels on a 120 MW pilot line. Renshine solar has recently announced 20.86% perovskite-Si tandem module (927.5 cm^2) with high stability awhile working on all-perovskite tandems at lab level.

In the USA, various companies including Tandem PV, Cubic PV and Swift Solar are garnering investments and working on bringing tandem devices to market.

Researchers have not yet settled on a standard 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) and three terminals (3T), the solar cells are operated independently, suppressing the need for current matching but requiring adapted module designs and structures. Voltage matched 4T modules are also a viable alternative, as voltage matching is less sensitive to the irradiation (i.e. very variable in bifacial installation).

Targets, Type of Activity and TRL

By 2030 tandem technologies is expected to reach a market share of more than 5% and successfully transition from niche to mass market applications. The technologies are expected to achieve long-term performance stability comparable to single-junction technologies, with clear advantages in terms of LCOE and the environmental footprint to be achieved thanks to efficiency benefits.

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 and modules.

Stable and cheap carrier selective contact materials for the hole and electron transport layers (HTL and ETL) have to be further developed. Furthermore, these layers should not lead to losses in terms of voltage (Voc) and fill factor (Rs).

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, Ag, Cs) 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.

[27] https://www.longi.com/en/news/is-m6-wafer-silicon-perovskite-tandem-cells-new-efficiency-record/

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 bifacial architectures.

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 of cells and 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 etc.).

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 bifaciality.

Flagship Actions (TRL7-8)

Pilot-line production of low-cost Silicon bottom cells derived from mature technologies such as e.g. hetero-junction, PERC, or technologies based on poly-Si passivating contacts such as TOPCon.

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.

Tailored module technologies for efficient interconnection and encapsulation of the cells, particularly adapted to the temperature restrictions. Development of measurement methods and stability procedures for analyzing cell and module performance and long-term stability

Develop **bifacial multi-junction perovskite PV devices** with suitable materials and suitable architecture to cope with large variation in irradiance on both sides (i.e. 4T structure), e.g. for future vertical PV elements in urban settings, 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 Voc deficit for top cell absorbers with Eg > 1.65 eV.

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

Develop low cost, wet processing of perovskite multi-layered junctions including use of sustainable materials for current collectors and charge transport layers.

Develop triple junction tandem cells

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.

PVD deposition tool with wafers after TCO deposition.

3.1.5
Roadmap 5: Other Tandem Technologies

Rationale for support

Tandem structures represent a significant opportunity for photovoltaic technologies that are currently struggling to achieve a path to industrialisation or large-scale market penetration with single junction devices. Exploring various tandem structures can also be highly relevant for specific applications with a more niche market potential, but suitable business perspectives.

Status

Multijunction III-V solar cells (based on III–V compound semiconductors) currently demonstrate the highest conversion efficiencies for non-concentrated (38,8 %) and concentrated (47,6% for 665 suns) illumination, they are usually limited to in concentrating photovoltaics (CPV) and space applications due to high manufacturing costs. The record efficiency for a three-junction cell is 44.5% from a InGaP/GaAs/InGaAs solar cell[40] Adding p-n junctions increases efficiency, e.g. to 47.6% at 665 suns in an inverted metamorphic six-junction cell structure based on III[41].

[40] *R.R. King et al. Band-gap engineered architectures for high-efficiency multijunction concentrator solar cells, 24th EUPVSEC, Hamburg, Germany (2009)*
[41] *M. Green et al., Solar Cell Efficiency Tables (Version 57), Progress in Photovoltaics 29 (2020)*

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.

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.

Terrestrial CPV should be re-evaluated considering new module concepts that can leverage the unique characteristics of concentrated light, such as the ability to utilize the DNI for multiple purposes in the same application including electricity generation, lighting, crop growing, etc.

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

KPIs for PV technologies with lower strategic industrial priority

technologies		KPIs for multi-TW deployment (2035)										other KPIs for lower maturity or different applications				
		EU manufacturing capacity				performance & reliability sustainability & circularity (aligned with challenge 2)				supply chain & materials (in agreement with Critical Raw Materials Act)		towards manufacturing & market needs		performance & reliability sustainability (aligned with challenge 2)		supply chain & materials (in agreement with Critical Raw Materials Act)
Architecture	materials	EU total production (GW) by 2035	% of EU materials in value chain (BOM & equipment)	pilot production (MW)	bottleneck	module efficiency (%)	LCOE (in medium irradiance level 1300kWh/m2a) Utility (€/MWh)	reliability (years)	bottlenecks	CRM reduction/ Suppression	bottlenecks	application	bottlenecks	cell / module R&D efficiency (%) TRL5 / (size)	reliability (years)	CRM reduction/ suppression
single junction	Thin film (organic/ kesterites)	N/A	>45%	N/A	N/A	N/A	< single junction Si	N/A	N/A	N/A	N/A	market identification for Kesterites	material/ interface limitations stability	18 / 30*30cm	25	no CRM
tandem	perovskite on perovskite	N/A	>45%	N/A	N/A	N/A	< single junction Si	N/A	stability , upscaling of absorber and charge-transport layers, scribing, lead management, outdoor performance validation, lack of standards, encapsulation	In, Ag	value chain for PK cells, material supply availability for TW scale?	develop the market for PK/PK based modules (iPV, climate?)	low band-gap PK development stability	30 / 30*30 cm	25	no CRM Lead issues?
tandem	III/V based	N/A	>45%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	material supply availability for TW scale?	to be defined, spatial?	material/ processes/ cost		25	no CRM

3.2
Objective 2: System design for lower LCoE of various applications

This objective focuses on the R&D needed for all other elements of PV systems besides the modules, notably the various pathways to improve the energy yield of systems (independent of the module technology used).

3.2.1
Roadmap 6: 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 low-cost energy. Various components of the system beyond modules and activities including installation, operation, maintenance, decommissioning, etc. (the so-called "soft costs") have an increasing impact on PV plant total 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 kWp).

Structuring efforts should be focused on improving reliability, durability, longer lifetime (challenge 2) 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 Eco-design Preparatory Study[42] 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 increase 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.[43]

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

[43] *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

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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.
- 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 handheld 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 40 years, similarly to PV modules or construction materials. Inverters should achieve operational lifetimes of at least 25 years.
Integrated Systems	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 to large PV systems.

3.3
Objective 3: Digitalisation of Photovoltaics

The advent of new digital technologies such as artificial intelligence, robotics and other tools allows for the emergence of entirely new solar business models and improve the profitability of existing systems and business models. 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).

3.3.1
Roadmap 7: Digitalisation of PV manufacturing

Rationale for support

Today's modern PV factories produce several gigawatts of wafers, solar cells and modules every year. Factories produce solar cells in the order of magnitude of billions per year per factory, requiring optimised processes to deliver products in time, at consistent quality and address potential issues. For competitiveness, digitalisation and automation of processes now is a requirement.

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. Digitalisation 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 standardised 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.

The application of digitalisation to manufacturing processes enables more accurate prediction of module failure rates or maintenance intervals. Systematically tracking PV power plant and component quality can deliver significant learning through the treatment of resulting data. **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 are expected to come line.

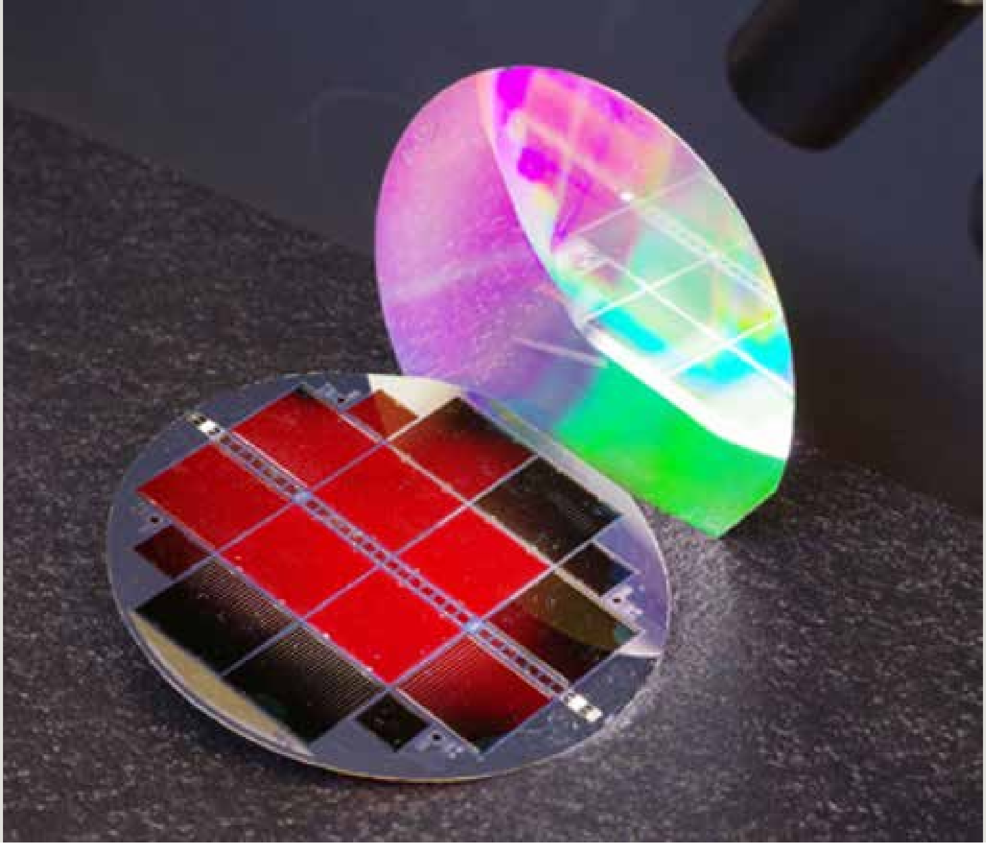
Generated data will be stored centrally requiring standard data representations and interfaces. Workpiece tracking will link single-wafers or carriers to their particular production parameters. The diversity of PV manufacturers products and users poses a key topic of standardisation of data to ensure the success of digital solutions. The use and sharing and exploitation of data represent regulatory challenges that also need to be overcome.

AI-supported software algorithms will scour data volumes for new connections and correlations to optimise production. Other applications of AI may include kits and largely standardized application packages for typical AI-based machine applications.

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.

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Development Research Actions (TRL 3-5)

Data generation:

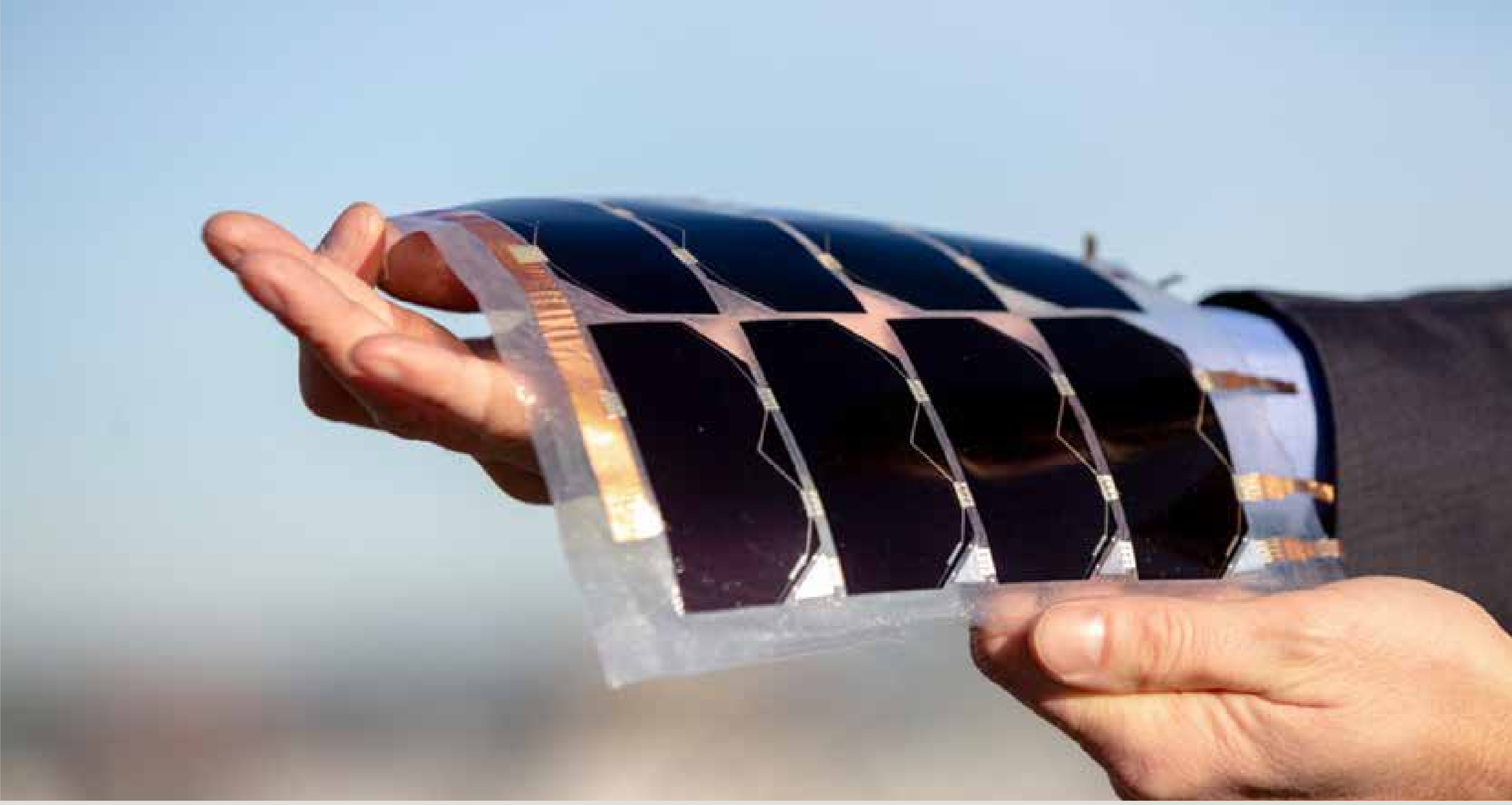
- Develop virtual and active identification processes and intelligent logistics components for material and device tracking across the value chain
- Develop fast and cost-efficient in-line measurement technology for real-time process control to widen the data base for machine learning in production.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

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.

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



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

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- 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.

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 or strategic 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. Eventually, the operation of a PV plant should guarantee in the future that 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 milestone of cumulative 1 TW goal was achieved in 2023. By the end of this decade a TW annual market could become a reality. PV already represents a share of more than 10% of the electricity generation in some countries (Italy, Germany and 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 viewpoints.

PHOTORAMA and 4 other European-funded projects TRUST-PV, RESiLEX, ICARUS, and CIRCUSOL have been working together to build a common message to enhance the sustainability and circularity of Photovoltaics Panels (PV). Through this alliance, they advocate for a better PV industry, fit for the challenges of the renewable energy transition. In the joint common policy brief titled "Advancing Photovoltaic Sustainability and Circularity in Europe"[44] they made 5 key contributions, drawn from the experience as projects working on innovative solutions for the photovoltaic (PV) value chain.

[44] https://www.photorama-project.eu/advancing-photovoltaic-sustainability-and-circularity-in-europe/

4.1
Objective 1: Sustainable and Circular solar PV

Recommendation 1 (by TRUST-PV):
Support development of an international standard to foster reuse of PV modules and grow a PV reuse market

Recommendation 2 (by PHOTORAMA):
Create a dedicated category for PV waste in the WEEE directive 2012/19/EU to adapt the collection/ recovery / recycling targets and incentivize recovery of valuable and critical materials

Recommendation 3 (by RESiLEX):
Support new and existing industries to ensure a fully European silicon value chain for the PV sector

Recommendation 4 (by ICARUS):
Support implementation of a full Circular Economy Framework for processing and refining PV manufacturing waste

Recommendation 5 (by CIRCUSOL):
Promote regulatory requirements incentivizing circularity and recovery of critical raw materials

Solar photovoltaic (PV) technology is one of the key engines for 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. That being said, it is certainly clear that production, transport, installation, EoL and operation of PV systems all require the consumption of materials and energy, and as a result, PV has an impact on our environment. We install PV to drastically reduce the high emissions of greenhouse gases associated with our current largely fossil fuel-based energy system. Although we know that PV is a renewable energy technology with a 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 that R&I efforts need to address. First, the environmental impact of manufacturing PV systems must be (further) minimized. Secondly, as the number of PV systems on the market rises, resource efficiency is becoming an increasingly critical factor for the long-term success of the sector. For PV to be sustainable and circular, continued R&D efforts are required along the PV value chain. A circular economy and renewable, clean energy need to go hand in hand to safeguard a truly sustainable transition towards a low-carbon future.

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.[45] 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 or strategic critical resources, where proof of concept of industrially feasible devices with alternative materials must be approached (by strategic critical resources it is meant as materials that are supplied by a only a few countries and are thus deemed as critical for the supply value chain for geopolitical reasons).

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

[45] *Groot, T. And Kishna, M., 2019. Outline of the circular economy. PBL Netherlands Environmental Assessment.*

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 η_{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, η_{grid} 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[46] show that, when η_{grid} increases to a value of 0.7 (which is the estimated η_{grid} in California in 2030 with a penetration of renewables of 80%) the ERoEIPE 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.
- System boundary: when reporting the environmental impacts associated with the generation of 1 kWh of PV electricity, it is essential to include a clear description of the system boundary of the analysis, and include not only the PV modules, but the full balance-of-system as well, to avoid underestimation of the total PV system environmental impact.

For more than ten years, the European Commission has been working together with several stakeholders to develop and update methods and datasets allowing companies to determine product environmental footprints (PEF) and organisational environmental footprints (OEF). The EC recommends the use of the EF3.1 method and database to determine the PEF for a broad set of environmental impact categories. It is important that the criteria used in the calculation are clearly stated and the boundaries for the calculation of the electricity supply are critically discussed. Although as said above the focus of PV LCA is commonly on greenhouse gas emissions and energy demand, the EF3.1 method includes a much broader set of impact, hence R&I on sustainable and circular PV should include all other impact categories.

[46] *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

Many of the R-ladder strategies will reduce the environmental impact in multiple or all categories.

4.1.1 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 results use life-cycle inventory data from 2023, assume production of PV in China, and module efficiencies of 20.9% for mono- and 18% for polycrystalline based PV, 18.4% for CdTe based PV, and 17.0% for CIS/CIGS based PV[47]. PV systems based on these technologies, when transported to and installed in a region of moderate insolation (1700 kWh m^{-2} yr^{-1}) have a carbon footprint of 28.7, 35.0, 20.21 and 28.5 gCO_2-eq/kWh, respectively for mono-Si, poly-Si, CdTe and CIGS based systems. Manufacturing, transport and installation of these systems releases a total of 1048 (mono-Si), 1276 (poly-Si), 738 (CdTe) and 1039 (CIGS) $kgCO_2$ per kWp of system capacity. The non-renewable EPBT (NREPBT) of these systems is around 0.80-0.96 years. It must be noted that the scientific literature presents a substantial variation in the life cycle environmental impact of module production especially, and that the knowledge on the manufacturing of technologies with a low market share (esp. poly-Si and CIGS) is somewhat outdated. A main driver for the variation in values reported for PERC and TOPCON mono-Si PV module manufacturing is related to the assumptions on the source of input electricity in manufacturing. Typical studies compare manufacturing in China (being representative for the current market) with that in Europe, for instance Germany or Norway. In the latter locations, the electricity mix is based on

[47] *Fact sheet Environmental Life Cycle Assessment of Electricity from PV Systems 2023 Data Update. M. Stucki, M. Götz, M. de Wild-Scholten, R. Frischknecht. IEA PVPS Task 12, 2024.*

[48] *A Strategic Research Agenda for Photovoltaic Solar Energy Technology. Edition 2. 2011*

[49] *International Roadmap for Photovoltaic (ITRPV), 2023 Results, 15th Edition. VDMA, 2023).*

[50] *Joel Jean, Patrick R. Brown, Robert L. Jaffe, Tonio Buonassisi and Vladimir Bulović. Pathways for solar photovoltaics. Energy Environ. Sci., 2015,8, 1200-1219*

[51] *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

higher shares of renewables (especially Norway), resulting in much lower emissions released in module manufacturing. Summarizing the latest state-of-the-art in LCA of PV, we can see:

- Typical system (based on PERC/TOPCON mono-Si modules) has an energy payback time in Southern Europe of around 0.8 years. The long-term potential is 0.25 years[48]
- Solar grade silicon consumption: 2.0-2.2 g/W (2023) [[49]], target <1.6 g/W in 2031 and beyond
- Non-cell general material intensity in 2018 (t/MW) (modules and BOS) [[50]]
  - 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 roof-mounted system in Southern European insolation, 1700 kWh/m2/yr, performance ratio of 0.8, and lifetime of 30 years: 28.7 gCO_2-eq/kWh.
- For thin-film technologies CdTe and CIGS, the carbon footprints under the same assumptions are 20.2 and 28.5 gCO_2-eq/kWh, respectively.
- 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 [[51]].
- 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 [[52]]

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/Wp) and improved module efficiency, both EPBT and carbon footprint have dropped by roughly an order of magnitude in the past 30 years. 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

[52] *„European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020"*

[53] *Louwen, A. Nature Communications volume 7, Article 13728(2016)*

[54] *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*

[58] *Estelle Gervais, Shivenes Shammugam, Lorenz Friedrich, Thomas Schlegl, Raw material needs for the large-scale deployment of photovoltaics – Effects of innovation-driven roadmaps on material constraints until 2050, Renewable and Sustainable Energy Reviews (137), 2021. https://doi.org/10.1016/j.rser.2020.110589.*

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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.

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.[54] Thus, it is clear that PV technology needs to keep improving over the entire value chain. 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 >100 g CO_2-eq/kWh towards lower values)[55] 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
  - Development of tandem solar cell technologies (Perovskite on silicon, on CdTe) that realize a higher conversion efficiency and have the potential to offer improved environmental impacts if long-term performance is guaranteed.
- Demonstration Actions (TRL 5-7)
  - Development of Cu-based contact systems
  - Use of recyclable polymers (PET, PP, PE, etc.)
  - Studies to evaluate and minimize the nighttime electricity consumption of PV inverters.
  - With high penetration of PV in grids, it becomes necessary to consider storage as part of the PV electricity supply.
- Flagship Action (TRL 7-8)
  - Reduced kerf loss in sawing
  - Favour the consumption of raw material produced in Europe, for example [56]:
    - 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

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 [57]:

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.

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

[57] *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)*

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.

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.

KPIs

KPI	Target value 2035	Current value
Energy required to produce MGS	< 8 kWh/kg	11 kWh/kg
Electricity for SoG silicon	< 40 kWh/kg	49 kWh/kg
Electricity for Cz ingot	< 25 kWh/kg	32 kWh/kg
Wafer thickness	100-140 µm depending on wafer size and type	150 µm (p-type) 145 µm (n-type, TOPCON ≥G12) 140 µm (n-type, TOPCON ≤M10) 130 µm (n-type, SHJ)
Kerf losses	45 µm	55 µm
Carbon footprint for a PV system including all components (modules, BOS) manufacturing, transportation and installation	Mono-c-S: (lifetime to 40 years) <12 gCO_2-eq/kWh <17 gCO_2-eq/kWh <28 gCO_2-eq/kWh PV tandem system < 12 gCO2-eq/kWh, Thin film single junction < 12 gCO_2-eq/kWh	Monocrystalline silicon (PERC/TOPCON) 20.9% 20 gCO_2-eq/kWh (2300 kWh/m², PR = 0.85, 30yrs) 27 gCO_2-eq/kWh (1700 kWh/m², PR = 0.85, 30yrs) 46 gCO_2-eq/kWh (1000 kWh/m², PR = 0.85, 30yrs) 36 gCO_2-eq/kWh (1331 kWh/m², PR = 0.83, 30yrs) Monocrystalline silicon (PERC/TOPCON) in average Europe (1331 kWh/m², PR = 0.83) 37.7 gCO_2-eq/kWh (China) 21.3 gCO_2-eq/kWh (Germany) 15.9 gCO_2-eq/kWh (Norway) TF: 14-46 gCO_2-eq/kWh
CED (MJ/Wp)	<10 MJ/Wp mono-Si	12.9 MJ/Wp mono-Si (PERC/TOPCON)
EPBT (non-renewable EPBT)	< 0.65 yrs for mono in Southern Europe	Monocrystalline silicon (PERC/TOPCON) 20.9% IEA PVPS Task 12 + ecoinvent + CHINA 0.56 years (2300 kWh/m², PR = 0.85, 30yrs) 0.75 years (1700 kWh/m², PR = 0.85, 30yrs) 1.28 years (1000 kWh/m², PR = 0.85, 30yrs) 1.00 years (1331 kWh/m², PR = 0.83, 30yrs)
EROI electricity kWh_{el}/kWh_{PE}		Monocrystalline silicon 20.9% IEA PVPS Task 12 + ecoinvent + CHINA 15 (2300 kWh/m², PR = 0.85, 30yrs) 11 (1700 kWh/m², PR = 0.85, 30yrs) 6.4 (1000 kWh/m², PR = 0.85, 30yrs) 8.2 (1331 kWh/m², PR = 0.83, 30yrs)
EROI primary energy kWh_{PE}/kWh_{PE} η_{grid}=0.3		Monocrystalline silicon 20.9% IEA PVPS Task 12 + ecoinvent + CHINA 49 (2300 kWh/m², PR = 0.85, 30yrs) 36 (1700 kWh/m², PR = 0.85, 30yrs) 21 (1000 kWh/m², PR = 0.85, 30yrs) 27 (1331 kWh/m², PR = 0.83, 30yrs)
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)	*Note that efficiency is a (additional) general lever for reduction of usage per Wp or kWh.*
Primary raw material usage	Silver: 50% reduction by 2035 Indium: Indium-free SHJ by 2035 18 kg/MWp (CIGS) 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)	Silver: 20 kg/MWp (PERC), 47 kg/MWp (SHJ) Indium: 6 kg/MWp (SHJ), 111 kg/MWp (CIGS)
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)	

4.1.2
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. H020 CIRCUSOL[59] 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.

The Terawatt Era of PV modules is approaching fast, and it is raising important questions about end-of-life management as up to 160 million tons of PV waste worldwide from 2016 to 2050 is projected by latest studies[60]. Based to the latest available (2022) figures reported on the growth of PV installations,[61] we can estimate that about 2-2.5 million PV modules are installed every day around the world and this number will steadily grow up to 5-5.5 million installed PV modules per day in an annual 1 TW market. With this in mind, and with an average annual failure rate of 0.2% in the field,[62] we may anticipate approximately 4 million PV modules to fail every year, corresponding to an annual weight of 100 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, revamping, insurance/contractual claims, etc., the cumulative PV waste is expected to reach up to 4 Mt by 2030. This figure is relatively modest compared to the expected cumulative waste of over 160-200 Mt by 2050[63]. 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.[64] 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:

[58] *Estelle Gervais, Shivenes Shammugam, Lorenz Friedrich, Thomas Schlegl, Raw material needs for the large-scale deployment of photovoltaics – Effects of innovation-driven roadmaps on material constraints until 2050, Renewable and Sustainable Energy Reviews (137), 2021. https://doi.org/10.1016/j.rser.2020.110589.*

[59] *https://www.circusol.eu/en*

[60] *https://www.nature.com/articles/s41567-023-02230-0*

[61] *Global Market Outlook, SPE, 2023-2027*

[62] *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.*

[63] *IRENA (2022), World Energy Transitions Outlook 2022: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi*

[64] *Circular Business Models for the Solar Power Industry" (CIRCUSOL); H2020-EU.3.5.4. [https://www.circusol.eu/en].*

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- 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, 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-use, repaired PV modules could serve as an essential source of spare parts for PV systems, ensuring their prolonged operations.

The PV installation boom started 15 years ago, which explains the natural emergence of the re-use market exploiting the first decommissioning wave. Re-use of PV modules is a nascent sector with companies operating in an uncharted and mostly unregulated domain with a business model that need to consider safety, performance, relabelling and warranty extension. The PV re-use market is growing with approximately 15 companies worldwide moving around 500-600 MWp (or 40000 tons) of PV modules yearly including 200 MWp/year in Europe.

Targets, Type of Activity and TRL

Early-Stage Research Actions (TRL 2-3)

- Analysis of repair and reuse potentials and evaluation/tracking of the level or repair and reuse

Development Research Actions (TRL 3-5)

- Design-for-recycling or design-for-circularity
  - ○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, including retrofittable backsheet materials
  - ○Coatings designed for repair and re-use
  - ○Self-healing materials and components
- Testing procedures and standards for second life of PV products (inverters, modules)
- Improved and increased PV plant testing and PV module performance characterisation before plant decommissioning

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)
- Validated, commercialised repair strategies/ methods for specific PV components (modules/ inverters)
- Deployment of automated on-site triage/ classification tools (software and hardware) of PV modules at large-scale (installed in PV plants) for early identification of PV modules candidates for repair/reuse/recycling.
- Incentives in European policies for reuse of PV modules, including clear targets and funds

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)
- Deployment of ID/tracking solutions at PV module level, reverse logistics, sorting/inventory of PV and warehouse operations

Technology

Early-Stage Research Actions (TRL 2-3)

Development Research Actions (TRL 3-5)

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 upscaled 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

System

Early-Stage Research Actions (TRL 2-3)

Development Research Actions (TRL 3-5)

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 C&I 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 provides 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.

KPIs

KPI	Target value 2035
% repair/reuse after EoL of first life PV	>50%
years of operation for reused modules	>10 years
cumulative lifetime minimum	Si = 40 years Pk = 25 years Tandem Pk-Si = 25 years
Milestone	
Demonstrate increasing amount of repair/reuse up to 50-60% and implementation of clear cost-effective triage protocols in the EoL sector for first life PV < 15 years	

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4.1.3
Roadmap 3: Recycle and Recover

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.[65]

Status

- End-of-Life recycling rate (EOL-RR) of Silicon (0%), Indium (<1%), Silver (~50%, excluding jewellery) [6]
- No recycling of polymers
- No / limited high value recycling of glass - end-of-waste criteria fulfilled, however, insufficient for reuse 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 polysilicon

The addressable volume (linked to market profit 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.

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) [[67]]

[65] *PV Quality and Economy (September 2018) https://etip-pv.eu/publications/etip-pv-publications/*
[66] *United Nations Environment Programme (2011). Metal stocks and recycling rates*
[67] *https://i4r-platform.eu/*

KPIs

KPI	Target value 2035
Recycling of kerf	recovery of about 40% of pure silicon (8N purity)
Recovery of polymers from PV module waste for chemical recycling	>90% recovery of PET, >99% PVF, PVDF >70% EVA
End-of-Life recycling rate (EOL-RR)	Silicon (>98%, 6N) Silver (>98%, 3N) Indium (>3N), >95% Copper (>95%, 3N) Ga (95%; 3N)
Delamination: material recovery after deframing and deboxing	>98%
Glass recovery	100% with antimony traceability[68]
Ecodesign criteria (ratio of recycled material)	>80%

[68] *Traceability means that glasses should be categorized according to their antimony composition with automatic detection or adapted design (certified 0% antimony content)*

4.1.4
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) that aims to scale up a strong PV manufacturing industry in Europe across the entire value chain from raw materials to recycling. and the European Solar PV Industry Alliance created in 2022, aims to accelerate solar PV deployment in the EU by scaling-up to 30 GW of annual solar PV manufacturing capacity in Europe by 2025, facilitating investment, de-risking sector acceleration, and supporting Europe's decarbonisation targets. [69]

The goal is to develop an industry to supply an annual capacity of 30 GW by 2025, adding 60 billion Euros of new GDP every year in Europe and creating more than 400,000 new jobs (direct and indirect)[70] working across all value chain segments including polysilicon, ingots, wafers, cells, modules and recycling.

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[62]. 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[62]. Designers and manufacturers should investigate ways of reducing both the energy and GHGs in production.[71]

Targets, Type of Activity and TRL

Early-Stage Research Actions (TRL 2-3)

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.

[69] https://solaralliance.eu/
[70] https://europeansolarinitiative.eu/
[71] *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.

KPIs

	KPI 2035	unit
Associated carbon emissions (for example using the French CRE ECS method):	<200	kgCO2eq/kWc
Renewable electricity used in manufacturing (%)	100	%
Reduction in Indium	>70	%
Amount of silver in solar cells: <10mg/Wp	<7	mg/Wp
Wafer thickness:	<120	mm
Use of recycled materials: global value in weight of PV module		%
Use of recycled materials: silicon		%
Reduced use of energy	30	%
Reduced use of water	50	%
Reduced waste/scrap: to be defined	x	%
Design for recycling in PV modules:		
Modules with An glass identified	100%	
Reliability	>40 (Si PV) >25 (Pk) >25 (CiGS) >30 (tandem)	years
Carbon footprint	< 12	gCO_2-eq/kWh

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4.1.5
Roadmap 5: Eco-labelling and energy-labelling

Rationale for support

As seen in Roadmap 1, 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) methodology and 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 [72] and developed sectoral Product Environmental Footprint Category Rules (PEFCR) for Photovoltaic Modules used in photovoltaic power systems for electricity generation [73]. 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 [74]
- Recommendations presented in the expert input paper – Eco-design & energy labelling for photovoltaic modules, inverters and systems in the EU [75].

Targets, Type of Activity and TRL

Early-Stage Research Actions (TRL 2-3)

Development Research Actions (TRL 3-5)

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 inverter 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.

[72] *Product Environmental Footprint (PEF) Pilot Phase, https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm*
[73] *PEFCR PV electricity v. 1.1; https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_v1.1.pdf*
[74] *Dodd, Nicholas; Espinosa, Nieves – JRC B5; Preparatory study for solar photovoltaic modules, inverters and systems, (Draft) Task 8 Report: Policy recommendations; December 2019*
[75] *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*

KPIs

<table>
<tr><th>KPI</th><th>Target value 2035</th></tr>
<tr><td>Lifetime in Eco-design</td><td>40 years for PV modules
15 years minimum for all electronic / electro-mechanical components of the inverter, including the software needed for the full function of the device.</td></tr>
<tr><td>PV module Degradation rate in Eco-design</td><td>0.4%/year</td></tr>
<tr><td>Delivery of the spare parts</td><td>Within 15 working days within Europe</td></tr>
<tr><td>EII classification</td><td>> 25 % Products (Modules & Inverters) with a minimum of “B”</td></tr>
<tr><td>Update of LCI database</td><td>Every year</td></tr>
<tr><td colspan="2">Milestones</td></tr>
<tr><td colspan="2">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 ...)</td></tr>
</table>

4.2
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[76], the COST Action PEARL-PV[77] or the H2020 project Solar Bankability[78] and TRUST-PV[79] 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[80] (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 accuracy 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.**

[76] https://iea-pvps.org/research-tasks/performance-operation-and-reliability-of-photovoltaic-systems/
[77] https://www.pearlpv-cost.eu/
[78] http://www.solarbankability.org/home.html
[79] www.trust-pv.eu
[80] https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3189

4.2.1
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[81]. 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[82]. 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)[83], Light and elevated Temperature Induced Degradation (LeTID)[84] or back sheet cracking[85] 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[86] 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 applies extended IEC testing for the 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[87] or CAST[88] tests. However, these approaches

81 https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/pv-status-report-2019

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

83 S. Pingel et al., "Potential Induced Degradation of solar cells and panels," in 2010 35th IEEE Photovoltaic Specialists Conference, Honolulu, HI, USA, Jun. 2010 - Jun. 2010, pp. 2817–2822.

84 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.

85 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.

86 https://www.pvqat.org/

87 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.

88 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

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

Early-Stage Research Actions (TRL 2-3)

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**

PV Module qualification

Flagship Actions (TRL 7-8)

- Combined or sequential 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 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

KPIs

KPI	Target value 2035
Proven lifetime of PV modules through extended testing	40 years for Silicon based technology, 25 for perovskite, 25 for CIGS, 30 then 40 for tandem Si-perovskite
Accuracy of yield assessments for new technologies and novel system design with uncertainty (1 sigma)	<5%
Milestones	
Establishment of European testing capacities for combined or sequential stress tests	

4.2.2 Roadmap 7: Quality assurance to increase lifetime and reliability

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.

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)
- Use of in-field robotics for fully automated workflows and continuous inspections
- Use of generative AI for fully automated O&M processes
- 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.

Drone surveying panels.

© Above Surveying

KPIs

KPI	Target value 2035
Inspected PV plants using (semi)-automatic EL/PL able to detect microcracks	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 2030 and 100 GW with at least 7 years of average operational time by 2035

4.2.1
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.solarbankability.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 reuse 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 2035
Typical WACC of utility scale PV	Reduced by 1 % compared to base level
O&M costs	Reduced by 33% thanks to optimisation in contracts
Milestones	
Define standardized contractual KPIs for EPC	
Define the warranty levels of modules, inverters and supporting structures with associated risks	

Challenge 3: New Applications through Integration of Photovoltaics (for Diversified and Dual-Use Deployment and Enhanced Value)

Photovoltaics is rapidly expanding beyond more traditional module structures as this energy technology expands and new applications become profitable. Thanks to the integration of PV into the built environment, our agricultural sector, or event floating on water, new surfaces and services emerge for the photovoltaic sector.These rapidly growing segments of the photovoltaic sector pose specific research and innovation challenges to enable their potential in terms of market uptake.

Some of these challenges are technological, to make sure that PV can perform optimally in an integrated environment – both from the perspective of energy production and for potential additional services provided by the PV system. To a large extent however, challenges related to PV integration also include a significant dimension linked to understanding the impact of these technologies in their implementation framework, and how to create market, standards and regulatory conditions that enables large scale development.

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

The inherent modularity of PV enables it to be installed in systems from Watts to Gigawatts. This allows PV to be integrated seamlessly into many different objects, products and applications, 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

5.1.1 Roadmap 1: PV in buildings

Rationale for support

It will be essential to decarbonize the energy used to construct and run buildings. 'Nearly zero energy buildings (nZEB) and Positive Energy Building (PEB) are being promoted by national and international regulations and require the integration of renewable energy systems. Decarbonisation is driving electrification, for example using 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, including fire safety regulations. 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. Education about PV integration is lagging behind in several countries for different professionals, starting from city planners through architects and building designers, and finally to installers and fire fighters. They need information about the effects of their decisions on solar yield on the one hand, and the safety cautions they need to take in their activities on the other hand.

Targets, Type of activity and TRL

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

The 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. Specifically, PV modules for building integration requirement an optimised approach to enable the performance of coloured module and ensure they can deliver high efficiencies.

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;

- 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)

Action IV: PV awareness for decision and policy makers in the built environment (TRL 8-9)

Engagement of the different actors (e.g. city planners, architects, building designers, installers and fire departments) that either affect or are affected by the PV integration in the buildings:

- 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)

Action IV: PV awareness for decision and policy makers in the built environment (TRL 8-9)

Engagement of the different actors (e.g. city planners, architects, building designers, installers and fire departments) that either affect or are affected by the PV integration in the buildings:

- city planners: effects of their decisions (on building heights and orientations etc) to the potential solar yield
- architects and building designers: placing and space availability of the PV panels, aesthetics and co-operation with rest of the energy system, limitations from e.g. fire regulations
- installers: how to deal with PV panels in e.g. façade installations
- fire fighters: how to deal with PV installations in case of fire incidents

KPIs

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

KPI	Target value	Year
Standardization		
Fire	Defined standards for fire safety characterization	2030
Building Code	Enhanced harmonization at European and National level on BIPV building component approval, enhanced harmonization on characterization methods for BIPV modules and systems and higher transparency and guidance for manufacturers to navigate through existing standard	2030
Energy Indicators	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 % while keeping addressing „BIPV competitiveness" indicators	2030
Cost		
Manufacturing	Increase manufacturing flexibility and mass customization approaches.	2030
Systems	Development of BIPV cost-effective solutions supported by advanced economic and business models for investors with PBT < 10 years.	2027
	BIPV system NPV > 0 including installations (assuming 10-15 year)	2030
Technology		
Aesthetics	Improved aesthetic options with higher color availability, improved and stable colors, enhanced efficiency for colored PV at reasonable cost	2030
Weight & Flexibility	Reduced weight and improved flexibility with wind load capacity necessary.	2030
Solar Windows	Semitransparent options for solar window	2030
Performance	Shadow resilience for a wider range of applications	2030
Circularity	Improved circularity: reuse through assembly and disassembly improvements, LCA driven design, operating lifetime > 35 years	2030
Data		
Digitalization	Reduction in project costs thanks to BIM/digitalization, Improved value chain process thanks to design for Manufacturing and design for Installation	2030

PV in Buildings.

© Zigzag

5.1.2
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 hence stands for a true added value to the vehicle.

VIPV remains an emerging application for photovoltaics integration, however the rapid trend towards electrification of transport is driving interest from OEMs towards this technology which provides benefits for range extension and other energy services that are becoming more relevant in BEVs. 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

PM Efficiency - SolarOnTop - Vos Logistics.

Solar on top.

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 available, mostly as prototypes. Many solutions exist for VAPV (vehicle-applied photovoltaics), where PV modules are mounted on existing vehicle surfaces after the vehicle has 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 expectations for it are 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 categorised 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 colours, homogeneity) must be fulfilled to significantly increase the social acceptance of VIPV.

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

KPI	Target value	Year
Standardization		
Performance Rating Methods	Methodology defined for accurate comparisons of systems in terms of additional power generation on a daily or monthly basis to help with customer understanding and comparisons. This must include differentiated use cases and understandable to customers.	2030
Homologation	Standards for Safety and Reliability to guide Road registration process in multiple countries.	2027
Vehicle Power Management	Shared and safe protocols defined for input to VPM for efficient charging while parked.	2030
Cost		
Manufacturing	Manufacturing concepts compatible with existing automotive supply chain requirements and processes including safety and traceability.	2028
System Additional Cost	Passenger Car: <800 EUR/m²	2025
	Passenger Car: <500 EUR/m²	2030
	Passenger Car: <250 EUR/m²	2035
	Commercial Vehicles: <400 EUR/m²	2028
	Commercial Vehicles: <200 EUR/m²	2035
Technology		
BOS	Development of power conversion electronics suited for dynamic irradiance and vehicle integration, and gamification of technology use.	2030
Battery Impact	Theoretical and real world validation of impact on battery longevity, recyclability and temperature management.	2035
Circularity	Improved recyclability, repairability, reusability, and recoverability to exceed EU ELV requirements at component level.	2035
New Technologies	Investigation of integration of new PV technologies into vehicle environment (i.e. thin-film resistance to partial shading, Pb-free perovskite, (semi-)transparency, tandems, etc.)	2035
Data		
On-road	Demonstrate and validate on-road performance and reliability in various environments.	2028
Grid/Infrastructure	Large fleet modeling with grid integration and pilot studies.	2030

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

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5.1.3
Roadmap 3: Agrivoltaics and landscape integration

Status

Agrivoltaics, in general, allow for the simultaneous use of land for both 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 and solar tracking capabilities. Such tracking systems offer more flexibility in light management for both agriculture and power generation, displaying a dual-yield control synergy unique to the agrivoltaics context. In comparison to other markets, European progress is significantly slower compared 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% by 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 agrivoltaics systems are increasing yearly.

Despite existing agrivoltaic systems showing promising results and the industry showing more and more interest in technology, the missing policies in most of the regions is holding back the expansion of 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.

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.

KPI	Target value	Year
Standardization		
Tools	Providing tools for easy design and integration of PV solutions for such new applications (e.g. software's)	2030
Permitting	Permitting processes definition and standardization (educated guesses to science)	2030
Cost		
Manufacturing	Progress towards high-volume low costs process for reliable integrated products with costs <1.5x cost of "utility" PV	2030
Installation	**Installation systems that minimize impact on land and production.**	**2030**
Technology		
PV and plant yield	Solutions that result in minimal or increased plant yield (> XX %)	2035
Biodiversity	Environmental impact evaluation and methodologies that can improve permitting time.	2030
Social	Studies to understand social aspects of agri-PV, food supplies, etc.	2030
Mounting Systems	Low cost and circular mounting system technology.	2035
Data		
Modelling	Detailed system modeling with comparable methodologies for biodiversity, plant yield as well as power generation.	2030

5.1.4
Roadmap 4: Floating PV

Rationale for support

Europe has 20,000 square kilometres of manmade reservoirs, on which 200 GWp 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 space in locations with a high population density or with low land availability. 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. Beyond this opportunity of sharing space, floating solar on dams for hydropower or in conjunction with wind energy induce synergies on the integration into the energy system. This is the concept of hybrid hydropower-PV projects operated as a single powerplant, or "Solar-Hydro" powerplant. They are particularly useful areas with less developed grid infrastructure, including rural areas, islands, or even areas in the process of electrification. They are also an opportunity to optimise the use of existing reservoirs for energy storage.

Status

Floating solar (FPV) is in rapid development, with globally close to 3.8GWp of installed capacity in the year 2021 and expected to be more than 4.8 in the year 2026. Approximately 400 MWp has been installed in Europe, of which 100 MWp in the Netherlands alone. Most installations are deployed on artificial waterbodies such as irrigation dams, industrial basins, water treatment plants, and unused mining pods. The major cost components of an onshore 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 (onshore or offshore in sheltered areas). For locations with higher waves some initial studies and pilots are underway. For the specific case of PV on hydropower reservoirs, standards that re-assure the owners of those plants and their regulators of the safety of floating PV arrays, and therefore on the safety of the dam itself, are needed.

Type of activity and TRL

- Floating solar on smooth water (TRL 8): activities needed on data collection on performance, O&M and 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 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.
- Methods to assess durability of floating substructures and of the modules mounted on them including if possible, via data collection from existing floating systems retrofitted (if needed) with strain gauges and other sensors; standards for floaters and modules based on these methods.

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

© Oceans of Energy.

- Standards for moorings, such that there is nearly no risk that they will break, creating flotsam,
- Develop and verify predictive yield models including dynamic behaviour of the PV including floats, temperature effects and wave induced mismatch losses, depending on the application environment (wave height class).
- Floaters standardisation
- Develop design rules for systems with proven neutral or positive ecological impact (including mitigating any depletion of dissolved oxygen in the waterbody; managing biofouling's impacts on PV systems and the local environment).
- Develop system designs for near-100% circularity, including the floating platform
- Modules resistance to mechanical stress induced by floating supports.
- Develop effective grid systems for floating solar in conjunction with wind energy, hydro and/or storage.
- Data collection: monitoring of FPV sites ideally both before and after floating PV is installed. By 2025, relevant ecological indicators to measure have been determined and measuring protocols defined.
- Define field of application for FPV on reservoir in accordance with risk analysis (floating debris, seismic loading, unprotected spillway, etc.)

KPIs

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

KPI	Target value	Year	
Standardization		Onshore	Offshore
Legislation/Permits	Wholistic standards for system design and installations based on environmental (biodiversity), economic, sustainability and social aspects.	2027	2030
Insurance	Safety standards and system standards to allow for insurance.	2030	2035
Cost			
LCOE	Onshore: Water savings and other dual usage to enable lower LCOE than terrestrial PV systems	2030	
CapEx & OPEX	Offshore: 100% more than terrestrial PV system with similar capacity		2032
	Onshore: 5% more than terrestrial PV system with similar capacity	2028	
Technology			
PV Panels	Designing robust and reliable solar modules including coating, encapsulations, back sheet appropriate for being contact with water, movement, and salinity	2030	2035
Lifetime	30 years for PV modules defined as 80% of initial performance (degradation ≈ 0,6%/year)	2030	2035
Structure	Designing new structure with fully/partially recyclable materials.	2030	
	Optimized structure including floater, mooring, and anchoring systems for higher performance, better heat transfer and robustness in both near shore and harsh conditions i.e. wave categories 3 and 4.		2035
Electronics	Designing higher IP electronics for offshore applications.		2030
	Robust and reliable energy transmission technologies (under water cable, hydrogen, etc.)		2035
Social and Community	Studies about accessibility and energy equity for FPV system deployments.	2030	
O & M	Optimization of operation and maintenance routines to decrease the frequency between failures, and maintenance (including cleaning)	2032	2035
Data			
Modelling	Methodology for dynamic inputs (i.e. irradiation, u-value, albedo, losses, etc.) for performance analysis compatible with commercial software like PV syst. to be used for system performance guarantee and yield assessments.	2030	2035
Data Logging	Data measurement and management from different climates zones and different technologies to be implemented for digitalization.	2030	2035

Photovoltaic Roofing for Motorways: Concept and deployment of a demonstrator for the generation of solar energy in the road infrastructure.

5.1.5 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	Year
Standardization		
Safety & Regulations	Framework and standardization allowing large scale development of infrastructure-integrated PV systems, including specific standards relating to IIPV (safety, glare, etc.)	2028
Cost		
LCOE	Development of cost-effective IIPV solutions supported by advanced economic models, with a focus on business models (private/public partnerships, concession, property rights, etc.)	2028
PBT	Payback time due to extra (manufacturing, installation, operation) < 50% of the lifetime of the regular (non-PV) infrastructure.	2032
Technology		
System Design	Panels: • Reliable, robust and cost-effective modules adapted to specific environments cases (e.g. integrated into the ground, or next to roads/railways) • Surface (front layer) of modules : resistance to damage due to projections (stones, etc.), soiling mitigation (from roads, graffiti, etc.) • Cost effective aesthetic solutions (e.g. transparency) Mounting: • Reliable, safe and cost-effective mounting structures (e.g. for retrofit of walls/ barriers, overhead structures) • Focus on exposure to damage and cascading effects (breakage, etc.) • Cost effective aesthetic solutions	2035
Linearity	Addressing the specific challenges of linear systems on long distances. Electrical connections over long distances can cause losses and high costs (of material, works and installation).	2030
Circularity	Quantification of benefits related to decreased land use due to exploitation of artificialized land (through LCA etc.)	2030
	Enhanced circularity through assembly/disassembly and maintenance improvement	2030
	Improved reliability towards operating lifetimes relative to regular infrastructure	2030
Social and Community	Synergy with energy sharing in the neighborhood around infrastructures (e.g. noise barriers)	2030
Data		
Digitalization	Dual use methodology/data management to maximize usage and application/impact on grid.	2035

5.1.6
Roadmap 6: „low-power“ energy harvesting PV

Rationale for support

Photovoltaic Energy harvesting in low light conditions such as indoors, or under artificial or diffuse light can be used to energize sensors, internet-of-things (IoT) devices as well other low-power electronics. Efficient energy harvesting combined with storage unit and low power electronics, can enable a wide application of autonomous sensors, domotics, remote monitoring etc.

Status

In low light, the light spectrum is significantly different with respect to the standardized AM1.5 spectrum and power densities is 2-3 orders lower compared to the standard 1 SUN intensity (1000 W/m2). Thus, conventional PV technology is not well suited for indoor applications. 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 rollout for commercial products. New generations of PV technologies have shown great potential in harvesting energy in low light conditions and lab demonstrations of PV cells with power conversion efficiencies above 40% at the small laboratory scale efficiency values have been shown for artificial indoor illumination on rigid and flexible substrates [K.S. Srivishnu et al. Solar Energy 264 (2023) 112057]

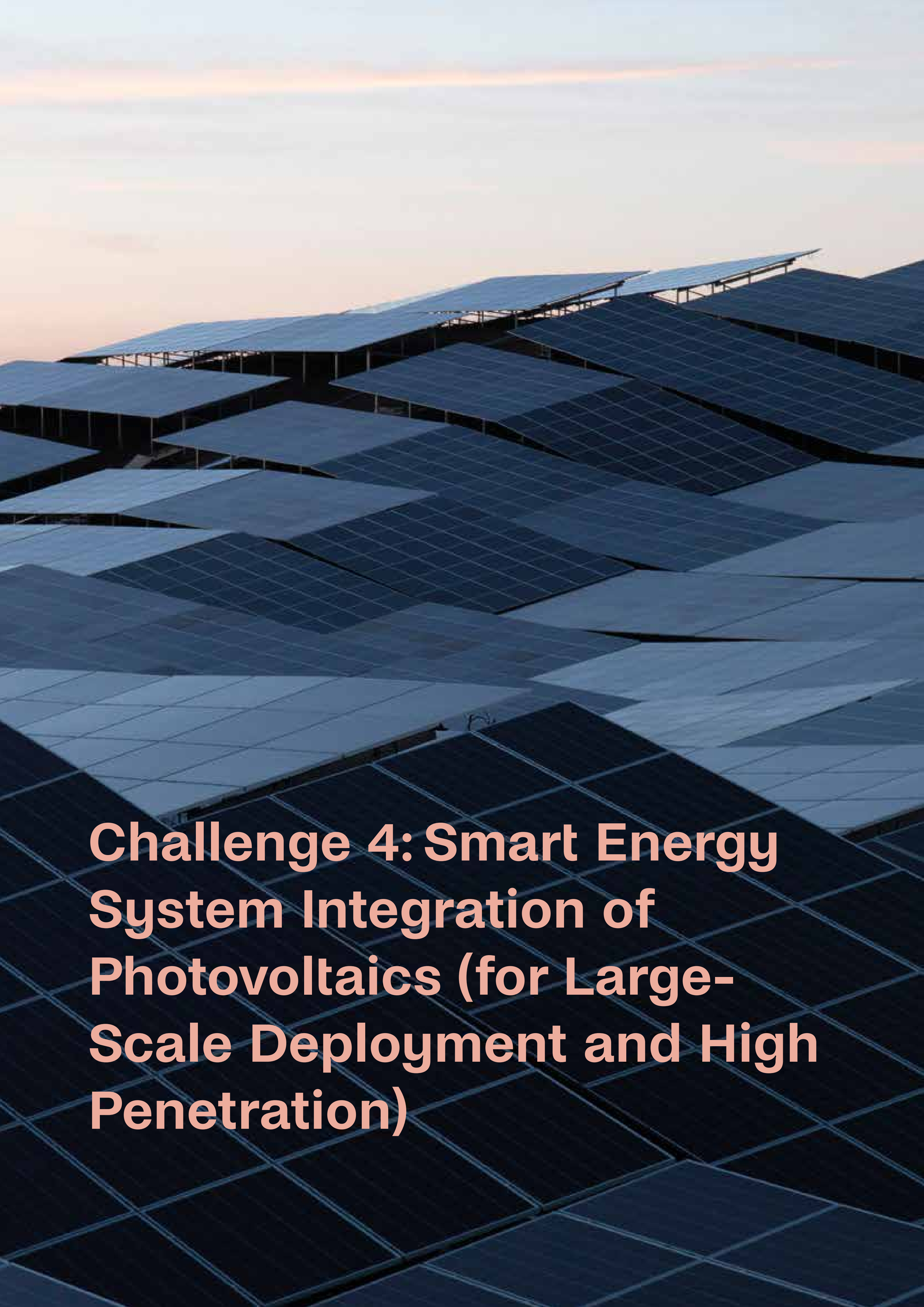
Targets, Type of activity and TRL

- Most of the development has been carried out on single cells. Series connected modules with voltages that can be utilized without boosters to power electronic products indoors need to be developed, by using cell technologies that show low leakage/recombination and maintain high efficiencies over module areas.
- Designs of module geometrical layout specifically for low light conditions are also sought as well as electrode materials with customized transparency vs. sheet resistance for low power/low current applications.
- 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, substrates used for packaging, ID, smart cards, 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).
- Develop novel concepts for module external electrical connections (TRL5).

KPIs

Only recently there has been some progress in developing device evaluation methods for indoor light quantification under low-light conditions that can be shared amongst researchers and operators (e.g. IEC TS 62607-7-2:2023 Technical Specification). But still more needs to be done including defining light sources, and there is currently no protocol for stability for indoors. The efficiency and hence the power density output however is strongly dependent on the spectrum, especially since the calibration is usually done in lux rather than in Watts. 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:

KPI	Target value
Design and Fabrication	Identification of PV materials and PV architecture and module design for the specific low power applications depending on the light intensity, light spectrum and application itself (2027) Module/cell design and fabrication process that enables easy tailoring of the PV device to product specifications.(2027) Understand the power and energy available in key environments (e.g. home, office, commercial buildings) and determine appropriate sizing of the PV elements as well as storage in relation to electronics operation (sleep, reading, transmissions cycles) in different applications (sensors and other IoT) (2027)
Performance	Power and energy yield PV performance to meet application specific power and energy requirements (2027) Stability (>80% of initial efficiency) under indoor illumination equal to lifetime of products for indoors (e.g. 5-10 years) (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 and/or batteries (2030) Integration of PV element monolithically with storage element (2027) Pilot production for low power PV capable of producing PV panels with various sizes and shapes (2030)



Challenge 4: Smart Energy System Integration of Photovoltaics (for Large-Scale Deployment and High Penetration)

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.

6.1 Identified needs and Objectives to develop seamless energy system integration

The document "A clean Planet for all"[89] 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 1.600 GW of solar PV power plants have already been installed worldwide [REF: IRENA latest report] where more than 400 GW were installed alone in 2023[90], 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 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 dispatch for new PV installations is expected to prevail as the lowest cost solution in all EU countries in the near future (it is already a market outcome in countries of the south such as Cyprus, Malta or Greece), the spread of PV systems including integration in the built and sealed environment could represent a new stable driving force for the diffusion of PV systems.

[89] *EUR-Lex - 52018DC0773 - EN - EUR-Lex (europa.eu)*

[90] *International Energy Agency - Photovoltaic Power Systems Programme; IEA PVPS, Task 1, Strategic PV Analysis and Outreach, Report IEA-PVPS T1-42:2024; ISBN 978-3-907281-55-0, (2024)*

PV is growing strong in independent applications at all levels and complexities: on roofs or facades 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 for improving the controllable flexibility and 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
- Improved efficiencies by integration of PV-systems in DC-networks
- Hybrid systems including demand flexibility (PV+ Wind + Hydro with embedded storage + batteries + green hydrogen/fuel cells + solar fuels/gas turbines & demand management)
- Aggregated electric power production and Virtual Power Plants
- Interoperability in communication and operation of RES smart grids.

6.1.1 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.

Intelligence will prevail in the interconnected system, with improved monitoring and controlling capabilities ranging over different system levels. 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. However, majority of the inverters used in normal residential installations do not have full voltage control capabilities enabled, simply due to less expensive structures.
- Limited quality, access, control or distribution to plant data as monitoring, plant status or availability as well as accurate real-time data for production.

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 modelling and data analysis (e.g.

physical, Digital Twins, machine-learning based models), 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.
- Improving the data quality, handling and modelling by digitalization and harmonization actions as basis for the integration of intelligence-based information for decision making facilitating PV-flexibilities and energy production in the integrated energy system.
- Model based system planning of long-term performance for topics of increasing relevance as climate adapted and climate mitigated production or better power-purchase-agreement planning

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 5 to 8 by 2027.
- Action 2: Technical development of inverter intelligence for providing frequency control moving TRL from 6 to 8 by 2028
- Action 3: Technical development of inverter capabilities for providing the grid forming capabilities far more widely, moving TRL from 5 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
Forecasting tools for PV systems to be widely available as a cloud service	By 2027: day ahead accuracy of 95% for 95% of the cases.
Forecasting tools for PV systems to be widely available as a cloud service with storage of 8% of energy generated within the planned day	By 2027: day ahead accuracy of 99% for 99% of the cases.
Smart inverters to be supportive to system control operations	By 2027: at least 5% of the generated energy and 50% of ground-based PV plant inverters to be equipped with grid forming functionality
Inverters to be more supportive for local system voltage control purposes	By 2027: at least 50% of new installed inverters capable for full P-Q control for voltage management
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.

6.1.2
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 distribution and transmission 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.

Due to the use of different DC voltage levels in final use, these applications will require DC/DC conversions, which are more energy efficient than traditional AC/DC conversions. Direct use of the DC energy generated is thus an obvious choice.

Based on these realities, more and more activities appear for enabling solutions for DC distribution grid, covering also emerging transmission needs and specialized applications (as e.g. PV plants of higher voltage levels).

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.

PV in Buildings.

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- 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.).
- Enable technology solutions at grid level using PV plants (modules, electronics, components) enabling integration options in a DC operated grid at different grid voltage levels

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 and micro grids 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 2029.
- Action 4: Development of DC solutions on component, plant and distribution grid (also micro-grid) level for improved DC coupling of PV plants to the energy system, moving TRL from 4 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
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 2027: 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

6.1.3
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 power and 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.

As RES penetration within the energy system 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 aiming for counterbalancing variations in production of a single source to a great extent (e.g. PV + wind).
- Adopt the generation profile of Hydro power plants with generation coming from PV systems and combine it with 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 as well as storage can offer higher total 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

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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.
- Hybrid systems can be considered at different system levels, ranging from small local microgrids to wider national systems. Local-level solutions are often implemented as energy communities, which primarily share the local resources optimally, but can also provide services towards higher energy system levels. The hybrid and aggregated systems at higher level might be aggregated assets or market zones and will offer and need new modes to define, plan, include and monitor their potential contribution and performance.

- Model based hybrid system planning for defined optimization goals (e.g. economical, ecological, performance, etc…) including ontological descriptive models, harmonization of operation models and data structures and evaluation routines, life-time models, risk assessment and modelling of market participation.
- All the models and innovative solutions will need for planning, analysing and O&M operation new services, methods, technical solutions and algorithms requiring higher quality data inputs from measurements and sensors with harmonized routines for calibration data handling and evaluation.

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 complex or integrated hybrid RES solutions for providing competitive energy using PV as one of the primary sources of energy moving TRL from 6 to 8 by 2027
- 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 with state-of-the-art storage systems (e.g. only battery) as well as complex and new system combinations (e.g. including hydrogen or more than one technology each on RES and storage side) moving TRL from 6 to 8 by 2027 as well as TRL from 5 to 7 by 2027 for complex systems.
- Action 3: Technical development of hybrid RES solutions using the flexibility of load including external storage systems and/or 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 2027: offering an LCOE price of the combined system lower than the prevailing wholesale price of several countries and islands in Europe.
Hybrid RES solutions to be developed using the added benefits of storage systems offering combined solutions with PV systems	By 2028: 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.

6.1.4
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 different market schemes.

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

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 and flexible assets 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 assets or 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 resources 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.
- Aggregated assets which might be medium of big PV parks other RES-flexibilities, or communal or building-integrated PV facilities must be able to use services, tools and methods in order to allow secure, reliable and plannable

market participation. Therefore, developments have to target enabling solutions for precise aggregation (and de-aggregation), forecasting and offering to markets including generalization and harmonization of methods for operation and control over the full lifetime of assets or plants.

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 and market participants moving TRL from 6 to 8 by 2027
- Action 2: Technical development of standardised operational models of energy communities and aggregated assets 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.

PV in Buildings.

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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 2027: capable of offering collective services to the system in an interoperable and harmonized way.
Standardised operational models of energy communities to be available	By 2027: facilitating the setting up and the operation of energy communities and aggregated assets (VPPs) as defined in the electricity directive and the requirements of DSOs and TSOs
The required hierarchical control of the integrated grid to be standardised	By 2030: facilitating the full energy system and market integrated operation of energy communities and aggregated assets (VPPs) in full compliance with the grid rules and the requirements of DSOs and TSOs.

6.1.5
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 standard application modelling concepts for power and energy systems,
- No existing model-based engineering concepts for energy applications in heterogeneous, distributed environments,
- Lack of interoperability between high-level grid control architectures (for instance SCADA systems) and low-level installations, leading to lack of information exchange between grids and buildings/local PV units/etc, hence inadequate observability.,
- Business and operation models lead to inefficient exchange of information; for instance, grid operations are limited by regulation and have no role in operating small-scale RES
- Gaps in the seamless operation of data acquisition, data handling transfer and storage as well as evaluation and modelling at plant level for gaining vital information for the gird control or planning of reserves at different voltage levels. Problems of data quality, data loss, sensor down time and sparse data events hardly exist today.
- 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. Overall, lack of interoperability between grid management systems and different inverter control systems makes this difficult as technologies stand. The quality and availability of ICT data for PV plants is hardly harmonized and not standardized. Approaches and harmonized methods for offering reliable and high-quality data for grid control, asset planning or status information are unitarily implemented or missing.

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 and harmonized 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 tackled35:

- Develop interoperability at inverter control level towards higher-level grid management 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, data structures, models, methods, tools and services for mission critical applications and reliable integration of PV assets into the energy system.

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 2027
- Action 2: Technical development of (harmonized) data structures and ICT solutions (e.g. communication protocol) allowing improved connectivity of PV system applications moving TRL from 5 to 8 by 2027.
- Action 3: Technical development 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 2027 to be available and in demonstration operational
Develop accessible source-based reference implementation of an open automation architecture for PV based and grid-oriented ICT solutions	By 2027 to be available and in demonstration operational
Develop a role-based access management for inverter-based DER	By 2027 to be operational
Fully interoperable advanced (remote controllable) inverter services with standardized and safe/resilient communication protocols	By 2030 to be operational

6.1.6
Roadmap 6: 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[91].

Field uptake of techniques for production forecasting (foremost among them operation and maintenance optimization, 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[92] and are usually limited to local predictions.[93] No accurate general regional model has been proposed to date.[94] 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%). [95]

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

[92] *Mellit, Massi Pavan, Ogliari, Leva, & Lughi, 2020*
[93] *S. Pelland, 2013*
[94] *Mellit, Massi Pavan, Ogliari, Leva, & Lughi, 2020*
[95] *Ibid.*

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.

Digitalization 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 optimization of PV modules production (Ghannam R., 2019) (Project SelFab Website, 2021)
- Operational Optimization (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 digitalization of PV modules and sensors integration it is expected that AI can play a significant role in automating the PV module operational optimization. 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.

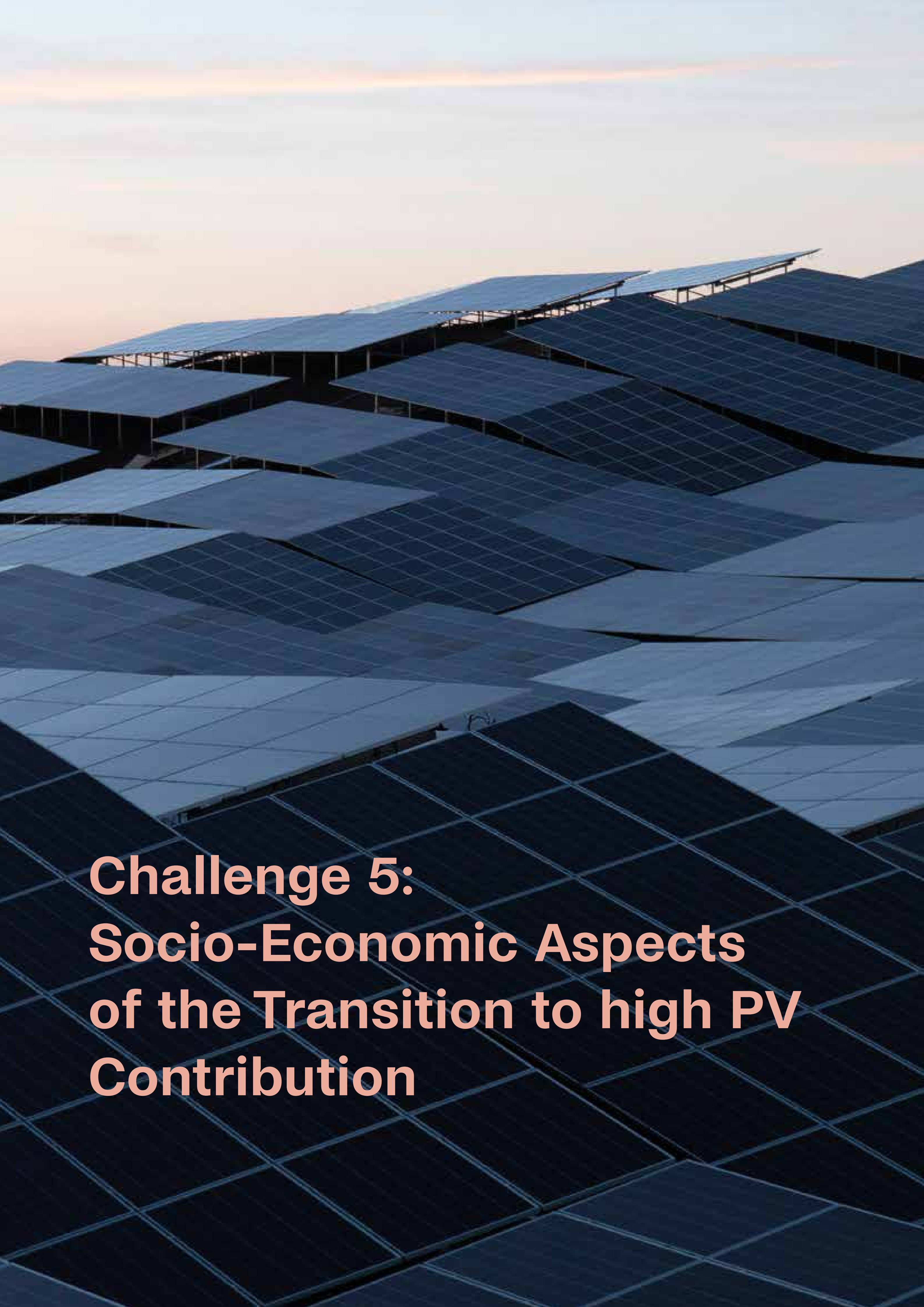
Development Research Actions (TRL 3-5):

- 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/Wp (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 5: Socio-Economic Aspects of the Transition to high PV Contribution

To achieve widespread deployment of solar PV and reach the EU's clean energy targets, it is imperative to address and overcome the significant socio-economic challenges that accompany this transition.

Recognizing the interdependence of these challenges is a key insight as addressing technological obstacles without considering the economic and societal aspects will become more and more of an incomplete approach. Therefore, challenge five of the SRIA addresses Socio-Economic Aspects of the Transition to high PV Contribution.

The Challenge is divided into three Objectives:

Objective 1: Acceptance of European PV deployment

Objective 2: Skills and Workforce

Objective 3: Environmental and Social Sustainability

These objectives cover the critical socio-economic dimensions needed to facilitate the transition to a high PV contribution, ensuring a comprehensive and inclusive approach to achieving Europe's clean energy goal.

7.1 Objective 1: Social Acceptance and Public Engagement

Decades of research highlight that social acceptance is crucial for the deployment of Renewable Energy Systems (RES) at all scales. Social acceptance, a complex outcome involving policymakers, businesses, NGOs, and citizens, depends on diverse factors such as socioeconomic, cultural, and institutional dimensions. Beyond social acceptance, active citizen involvement, especially as prosumers (those who consume and produce renewable energy), is vital for a successful energy transition. Objective one highlights the need to enhance social acceptance and promote active citizen involvement in the deployment of PV

7.1.1 Roadmap 1: Acceptance of European PV deployment

Rationale for support

Community and Market Acceptance are critical factors in determining whether households and communities are receptive to the adoption of PV technologies. PV deployment can take various forms, such as residential installations, or utility-scale projects. Therefore, it is important to explore the acceptance of these different deployment types, as the factors influencing acceptance may vary.

Acceptance of solar PV at the residential level is influenced by factors like investment costs, information availability, and the potential to save on energy bills. Homeowners, as consumers, may consider solar panels if they are well-informed about the technology and see financial benefits[96].

[96] https://doi.org/10.1016/j.esr.2023.101178

PV in Buildings.

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Large-scale solar PV projects often involve substantial investment, regulatory considerations and relevant impacts on the local landscape and other environmental aspects (e.g. biodiversity., contrast with other land uses...[2]) Acceptance in this case may result from a careful balancing of impact minimizing measures, through proper engagement strategies (see chapter 2) with incentives from economic viability, job creation, and the many environmental benefits of clean energy generation from PV.

The Acceptance of European PV deployment is therefore a multifaceted concept, shaped by various factors interplaying at different levels of the energy system. Understanding these barriers and tailoring strategies to address them is crucial in promoting the broader adoption of solar PV technologies across different sectors and regions. Policymakers, industry stakeholders, and advocates must work collaboratively to overcome these barriers through an effective engagement of the final users and citizens in order to advance the transition to clean, sustainable energy sources.

Status

For the deployment of Residential PV several key barriers hinder widespread residential PV adoption, including low information availability, financial concerns, and sociodemographic factors. The Horizon Europe project SunHorizon identified these as significant factors affecting acceptance[97].

Targets, Type of activity and TRL

Residential PV Deployment:

- **Increasing Environmental Awareness:** Raising environmental awareness among residents is imperative. Individuals with a strong environmental consciousness are more likely to adopt PV systems and support the transition to clean energy.
- **Information Campaigns**: Comprehensive information campaigns are essential for increasing stakeholder knowledge about residential PV systems. Access to accurate and detailed information is crucial for overcoming information barriers to adoption.
- **Recouping Investment Costs**: Providing clear information on the financial aspects of PV systems is vital. Demonstrating how investments in PV technology can be recouped over time helps alleviate concerns regarding high upfront costs.
- **Tackling Social Acceptance Issues:** Low social acceptance of residential PV may be linked to perceptions of high investment costs, long payback periods, and the absence of viable business models. Therefore, dissemination activities should focus on addressing these issues, including innovative PV system demonstrations and feasibility studies. Supportive policies, such as grants or loans, can help shift attitudes towards the financial aspects of PV technologies.

Utility Scale PV:

- **Net Congestion Solutions:** Cable Pooling (combining solar + wind), battery storage and/or green hydrogen production, direct consumption and/or mini grid, flex connections of distributed generation solar PV projects, facilitating permits for TSO and DSO to fortify the grid, decentralized energy production, government mandate for PV projects to balance and maintain the health of the grid
- **Forecasting and Curtailment:** Out of the box solutions, multi-stakeholder inter and intra-communication, long term policy support and approaches to implement to be deemed viable for investors to dive into like battery storage, green hydrogen production.
- **Standardisation and acceptance of new applications:** Learn from the success of implementation of floating and/or agrivoltaics in certain regions and which crops benefit most, added value by government tenders in combining food and energy and/or dual use of land to compensate for the higher CAPEX costs in new applications like agrivoltaics and floating.
- **Permit Processes:** Implementation tools and lessons learnt from the EU commission Renewable Energy Directive to reduce permit times from countries that have implemented it with success.
- **Local Acceptance:** Crowdfunding for PV projects, information sessions, requirement for nature inclusivity & biodiversity, sheep grazing and bio-diversity friendly mowing policies that are a must have to obtain permits for realization.

[97] *Social and market acceptance of photovoltaic panels and heat pumps in Europe: A literature review and survey - ScienceDirect*

KPIs

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

KPI	Target value 2035
Availability of regulatory framework for PV deployment	Comprehensive regulatory frameworks established and operational in key European countries to support seamless PV deployment
Wide adoption of best practices for stakeholder engagement	Extensive adoption of internationally recognised best practices for stakeholder engagement in the majority of European countries, ensuring community and market acceptance
Implementation and diversification of solar PV applications (agrivoltaics, floating, rooftop, BIPV, ground projects, etc.)	Significant implementation and diversification of innovative solar PV applications across various geographical and socio-economic contexts within Europe

7.1.2
Roadmap 2: Acceptance of novel true-cost pricing grid tariff schemes

Rationale for support

Electricity consumption is mostly demand-driven, i.e., independent of the load situation in the distribution grid or the upstream distribution grid and is hardly influenced by the current and local supply of electricity from renewable energy sources such as PV. This independence of electricity consumption from locally available grid resources and the time-varying nature of energy production from PV leads to both technical and economic inefficiencies, resulting in avoidable costs and technical-organizational challenges for the electricity grid. This decoupling of the grid tariff from the local situation also has disadvantages for electricity consumers and producers:

Consumers with existing flexibility potentially lack both the economic incentives to activate this potential and the information about when and how much flexibility would be of benefit to the system. This economic aspect is reinforced by a factor that is particularly relevant for households when deciding to produce renewable energy (e.g., by installing a PV system): the intention of many prosumers is to produce electricity for their own and local consumption and not for supra-regional distribution. Grid tariffs are a promising instrument to counteract the decoupling of the consumption behavior of consumers and the situation in the local electricity grid or the current production level from renewables, thereby contributing to better coordination of all elements in a local electricity system.

Status

In the European Union, each of the 27 countries employs different grid tariff systems, which typically include one or more of the following components: a fixed lump-sum, a volume-based charge per unit of energy, and a load-dependent charge based on capacity provided or demanded. A recent survey of European energy experts found that 90% believe incorporating a load-dependent component is essential for future grid tariff systems[98]. Despite this, no country mandates load-dependent tariffs based on actual measured power at the household level through smart metering, even though such tariffs can enhance grid stability and reduce infrastructure costs.

Implementing load-based grid tariffs poses challenges for social acceptance. These tariffs may redistribute costs, potentially benefiting high-consumption (often higher-income) households, while disadvantaging low-consumption households[99]. Households may need to alter consumption patterns to avoid higher costs, which could be difficult. Additionally, electricity grid providers and electricity markets may send conflicting signals to consumers due to their different priorities—grid stability versus cost-effectiveness—leading to confusion and potential resistance.

These factors make the social and political acceptance of load-based tariffs challenging, as the financial impacts on consumers are complex and the characteristics of potential winners and losers remain unclear. This complexity can hinder the adoption of more dynamic and cost-reflective grid tariff systems.

[98] *Nebiolo, Stefano. (2021) The evolution of residential network tariffs in Europe - the opinion of energy experts.* [*https://bit.ly/3pvlpTp*](https://bit.ly/3pvlpTp)

[99] *Azarova, Valeriya et al. (2018). Exploring the impact of network tariffs on household electricity expenditures using load profiles and socio-economic characteristics. Nature Energy 3, 317–325.*

Targets and activities

Future Grid Tariffs:

- Reflect actual grid usage.
- Potential designs include:
    - Abolition of fixed components.
    - Load-based prices based on daily or monthly 15-minute load peaks.
    - Integration of additional price signals based on local PV production forecasts.
    - Support for maximizing self-consumption through: Energy communities, self-generation and self-storage, feed-in tariffs, electric mobility, collective generation systems in apartment buildings.

Further Research:

- Determine optimal tariff systems under different circumstances.
- Assess how different tariff structures affect households and costs differently.
- Communicate to consumers: How their consumption patterns impact the local grid, importance of timing and intensity over volume, benefits of true-cost pricing, such as reduced grid infrastructure costs and increased renewable energy integration.

Figure 1 displays an exemplary load profile of a consumer under one possibility of a true-cost pricing grid tariff system. The low tariff grants a discount during times of high supply (e.g., high local PV production), if the consumer exceeds a certain minimum load threshold (e.g., 2 KW). The high tariff is active during times of high demand, if the consumer exceeds a certain maximum load threshold (e.g., 4KW). This example includes the possibility to vary feed-in tariffs based on the local grid situation.

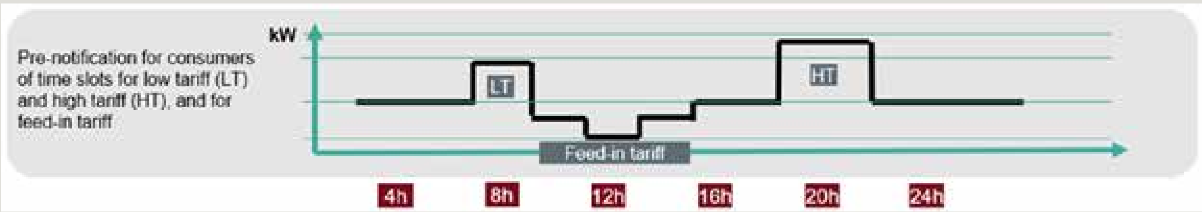


Figure 1: Example of a true-cost grid tariff system (Source: Own depiction based on tariff-ideas that are being investigated within the project INNOnet[100])

[100] https://projekte.ffg.at/projekt/4478292

KPIs

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

KPI	Target value 2035
Level of consumer awareness and understanding of load-based grid tariffs, renewable energy integration, and the benefits of true-cost pricing.	Achieve a high level of consumer awareness, with at least 80% of electricity consumers demonstrating understanding of how their consumption patterns impact the local grid and the benefits of true-cost pricing.
Share of countries within the European Union that have implemented load-based grid tariffs at the household level. It reflects the extent to which load-based tariff models have been adopted and integrated into national energy policies and regulatory frameworks.	Ensure widespread adoption of load-based grid tariffs, with at least 75% of countries within the European Union applying load-based tariff models at the household level.
Share of consumers actively adjusting their consumption patterns in response to load-based grid tariff models. It reflects the effectiveness of these tariff models in incentivizing behavior change and promoting grid efficiency.	Achieve a substantial increase in consumer engagement, with at least 50% of electricity consumers actively adjusting their consumption patterns in response to load-based grid tariff models.

7.1.3
Roadmap 3: Citizen's participation in PV Deployment

Rationale for support

The role of citizens in accepting and adopting PV technologies is crucial for their widespread use.The high market penetration potential of PV relies on its modularity and its applicability across different market segments. In 2022, small to medium-scale rooftop PV installations were the largest source of PV deployment in Europe, a trend expected to continue[101]. Achieving these targets necessitates the involvement of actors beyond large companies, such as citizens, SMEs, and local authorities.

Despite the benefits, citizens often hesitate to adopt new technologies like PV due to a lack of awareness and knowledge. Barriers to participation include financial constraints, lack of time, and trust issues among neighbors. Furthermore, satisfaction with the current energy system often demotivates citizens from investing in PV systems[102].

Status

Currently, business models facilitating citizen participation in the energy transition include energy communities, aggregators, and crowdfunding platforms. These models enable consumers to take a more active role in developing renewable energy projects. Energy communities empower citizens by allowing them to purchase, share, and co-own energy projects, and to choose how their capital is used[103].

Energy communities have been growing across Europe, particularly in Germany and Italy, where generous Feed-in Tariff policies have made PV investments more approachable. However, their share of total PV installations remains relatively small[104]. The evolving European policy and regulatory framework, including the Renewable Energy Directive (RED II) and the Internal Electricity Market Directive (IEMD), has provided a legal definition for energy communities and spurred increased interest in their development[105].

Renewable energy aggregators, or „digital utilities," aggregate prosumers and consumers to negotiate better deals in the wholesale energy market. They are increasingly seen as the utilities of the future, enabling more competitive and affordable electricity for their members[106].

Targets and Types of Activities

Active citizen engagement (e.g. through energy communities) and social ownership (e.g. through energy cooperatives, crowdfunding) should be increasingly accounted for in defining and analyzing drivers of social change toward low carbon economies and society. Indeed, social innovation is a key element to support uptake of new low carbon technologies as well as behavioral change and paradigm shifts in the energy transition.

The new European policy framework (provisions in EU Directive 2018/2001 (RED II) and 2019/944 (IEM) has created the conditions for the uptake of energy communities and self-consumption schemes, but further work and analysis is needed to support a widespread and even deployment across member states as well as to maximize citizens participation and positive impacts for the communities involved, including:

[101] *"EU Market Outlook For Solar Power 2022 – 2026", Solar Power Europe Report https://www.solarpowereurope.org/insights/market-outlooks/eu-market-outlook-for-solar-power-2022-2026-2*

[102] *Putting people at the heart of the energy transitions. Policy brief prepared by the EU H2020 Projects Comets, Newcomers, SocialRES and SONNET: http://socialres.eu/wp-content/uploads/2022/05/H2020_Policy-brief_final.pdf*

[103] *Lupi V., Candelise C., Almuni Calull M., Delvaux S., Valkering P., Hubert W., et al. "Characterization of European Collective Action Initiatives and Their Role as Enablers of Citizens' Participation in the Energy Transition" Energies 2021 Vol. 14 Issue 24*

[104] *Candelise, C., Ruggieri, G. 2020. Status and Evolution of the Community Energy Sector in Italy. Energies, 13; Wieling at al 201, Ibidem*

[105] *Candelise C, Ruggieri G, 2022, The Community Energy sector in Italy: historical perspective and recent evolution, Renewable Energy Communities and the Low Carbon Energy Transition in Europe, Editors: Coenen, Hoppe, Publisher: Palgrave Macmillan, ISBN: 9783030844394*

[106] *http://socialres.eu/*

- Monitoring, assessment and evaluation of the effectiveness of the transposition process in the EU member states of the energy community policy framework defined by the EU Directive the Renewable Energy Directive (RED II) and the Internal Electricity Market Directive (IEMD).
- Study and assessment of whether and how the different implementation models of energy communities and self-consumption schemes developing across member states are delivering in terms of citizens participation, energy democracy and collective benefit of providers and users.
- Development of indicators and data collection to assess performance of energy communities and their economic, environmental and social impacts. Data collection and evidence elicitation on impacts of citizens participation to the energy transition is needed to inform evidence-based policy making and support.
- Study and elicit evidence on the potential of energy communities and self-consumption schemes to help in overcoming energy poverty. Enhance the role of local authorities as enabler as well as active actors of energy communities' deployment and more generally to citizens and communities' engagement in the development and the implementation of energy projects.

Study of the design and the implementation of energy communities and collective self-consumption schemes integrating different generation technologies as well as storage and electric mobility in order to:

- Better respond to local community needs;
- More efficient system sizing;
- Improving economics of the project, thus increasing economic benefits for members and communities accruing from the project well as profitability of the investment;
- Explore and assess the interaction of energy community with the grid and their potential to provide power flexibility.

Securing funding can be a barrier for energy communities' development, in particular for those developed with bottom-up approaches and citizens led, which might lack resources and skills to access traditional finance. Crowdfunding is an alternative source of funding which could help in responding to this challenge, while also enhancing citizens' involvement through participation in investment and energy assets' ownership. Evidence from previous studies have indeed shown how citizens have played an important role in providing initial finance to new energy communities[107].

More generally, crowdfunding is increasingly used in Europe to finance energy project through citizens and diffuse investors' participation. However, up to date, aggregated evidence on number and type of funded projects, number of citizens involved as well as total funding raised is missing or needs updating[108]. This evidence is crucial to support further and needed analysis on:

- the potential of energy crowdfunding in mobilizing private capital and in contributing to achieving the investment needed to reach the European Green Deal ambitions;
- its potential in terms of citizens participation, and financial access and redistribution.

KPIs

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

KPI	Target value 2035
Number of energy communities or PV capacity installed	A significant increase in both energy community deployed and relative installed PV capacity is expected by 2035
Number of PV projects financed in crowdfunding and number of citizens investing in PV through crowdfunding	Number of PV projects financed and number of citizens investing in PV projects through crowdfunding is expected to significantly increase by 2035
Number of aggregators active in Europe	A significant increase in the number of aggregators is expected by 2035

7.1.4
Roadmap 4: Socio-economic dimensions impacting decisions to implement and use PV technology

Rationale for support

Adoption of PV systems is influenced by a variety of factors including affordability, technical aspects like the reduction in LCOE, (biospheric) values and social influences. Economic drivers such as return-on-investment expectations and the perceived contribution to emissions reduction play a key role. Informative and normative social influences from peers who have adopted or rejected PV systems can impact perceptions and individual decisions.

Behavioral adaptations are crucial for energy sector changes and policies. These behaviors range from expensive investments like home insulation to habitual actions such as transportation choices, and collective actions like participating in community heat networks. Keeping these behavioral aspects in mind is essential for the successful adoption of PV systems.

Status

Understanding and modeling the behavioral response to energy policies are vital for estimating their potential impacts. Traditional economic models are focusing on individual choice behaviour, and often fall short in capturing the complex social and behavioral dynamics involved, especially in community projects (social innovation). Agent-based models (ABMs) have emerged as a more effective tool, simulating how heterogeneous agents interact within a community and influence each other under different policy scenarios .

ABMs can model individual behaviors and social networks, helping to study the diffusion of innovations, identify barriers, and explore tipping points. These models have been applied to various energy-related behaviors, including the adoption of PV systems, electric vehicles, and energy-efficient technologies. Integrated models combining multiple behavioral theories offer deeper insights into energy-related behaviors and can be connected with other energy models to develop more realistic scenarios of technological diffusion and behavioral changes[110,111].

In addition to ABMs, macroeconomic modeling combined with technical engineering models can provide crucial insights into the impacts of PV adoption. Randomized Controlled Trials (RCTs) can also be valuable for evaluating the socio-economic impacts of PV adoption in specific contexts, such as agrivoltaics.

Types of activities/targets

The following activities are recommended with a view to improving the understanding of how socio-economic factors influence agents' behaviors:

- Systematic inclusion of socio-economic analysis in PV-related calls. Make reference to the concept of SRL as much as possible in the calls.
- Assessing the socio-economic aspects using both qualitative and quantitative methods
- Quantification of socio-economic criteria.
- Systematic inclusion of stakeholders' analysis in the development of PV technologies at different levels: from proposed technological solution, to testing, validation, and demonstration.
- Define models to consistently integrate stakeholders at different levels of development of PV technologies.
- Proposals should include a plan for social adaptation.
- Adopt, as much as possible, co-creation processes with stakeholders.

[107] *Lupi V., Candelise C., Almuni Calull M., Delvaux S., Valkering P., Hubert W., et al. "Characterization of European Collective Action Initiatives and Their Role as Enablers of Citizens' Participation in the Energy Transition" Energies 2021 Vol. 14 Issue 24*

[108] *Candelise C, 2018, Crowdfunding as a novel financial tool for district heating projects, „Crowdfunding as a novel financial tool for district heating projects" study under H2020 project TEMPO (Temperature Optimisation for Low Temperature District Heating across Europe)., Brussels*

KPIs

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

KPI	Target value 2035
PV-related calls incorporating socio-economic analysis	Majority of PV-related call including socio-economic analysis and impact assessment
PV projects assessing socio-economic aspects using both qualitative and quantitative methods	PV projects incorporate a balanced mix of qualitative and quantitative socio-economic assessments, ensuring holistic evaluation.
Quantification of Socio-Economic Criteria	Implementation of robust methodologies for socio-economic quantification, contributing to clearer and more actionable insights.

[110] Social norms as solutions | Beijer Institute (kva.se)
[111] (PDF) Sensemaking of causality in agent-based models (researchgate.net)

7.2
Objective 2: Skills and workforce

The rapid expansion of the European solar industry demands a highly skilled and diverse workforce to sustain its growth and meet ambitious renewable energy targets. Addressing the existing skill gaps and promoting gender equality within the PV sector are crucial for creating a resilient and innovative labor force.

Objective two focuses on advancing the workforce development in the PV industry and emphasizes the need for gender equality to ensure a balanced and inclusive workforce, thereby enhancing the sector's productivity and innovation potential.

7.2.1
Roadmap 5: Re-skilling and Up-skilling in the PV sector

Rationale for support

The European solar industry is poised for substantial growth, driven by ambitious targets and increasing demand for renewable energy. The sector is expected to create significant employment opportunities, particularly in roles such as design engineers, electrical engineers, and construction workers. However, The rapid expansion of the European solar industry demands a highly skilled and diverse workforce to sustain its growth and meet ambitious renewable energy targets. Addressing the existing skill gaps and promoting gender equality within the PV sector are crucial for creating a resilient and innovative labor force. Objective two focuses on advancing the workforce development in the PV industry and emphasizes the need for gender equality to ensure a balanced and inclusive workforce, thereby enhancing the sector's productivity and innovation potential. labor pose a critical challenge, threatening to impede this growth. To address these gaps, robust re-skilling and up-skilling initiatives are essential. These efforts aim to equip both existing professionals and individuals from diverse backgrounds with the necessary skills to meet the evolving demands of the photovoltaic (PV) industry.

Status

As of 2023, the European Union's solar sector is experiencing rapid expansion, with projections indicating the creation of up to 1.2 million jobs by 2027, up from 648,000 in 2022[112]. The demand for skilled workers is particularly acute in key roles essential to solar deployment, such as product engineers, electrical engineers, and construction workers. Challenges include fierce competition for specialised roles, declining STEM student enrollments, and insufficient workforce preparedness. These factors underscore the urgency for targeted interventions to bridge the skills gap and ensure a capable workforce for sustained industry growth.

Types of activities/targets

- **National Assessments of Skills Gap:** As mandated in REDIII, Member States should invest resources in identifying workforce gaps and skill sets more comprehensively. Regular gathering of precise information for various professions is essential to establish a European plan of action for skills.
- **Communication & Education Campaigns on Green Collar Jobs:** European education policies should shift to better value manual careers, communicate the need for green jobs, and provide training opportunities. Manual careers should be more highly valued among

[112] EU Solar Jobs Report 2023 - SolarPower Europe

students and job seekers, with efforts directed at education professionals, public and private employment platforms, VET providers, and local authorities.

- **Specialised Training for Relevant Professionals:** The training of electricians and construction workers for solar installations should be accelerated, ensuring high-quality work and safety. This specialization will lead to better-equipped workers for the growing solar industry.
- **Retraining Programs for the Just Transition:** Lifelong training should be encouraged, especially for transitioning industries, with programs developed to prioritize workforce reconversion in jobs needed for the clean energy transition.
- **Skill-Proofing Energy Policies:** Integrated renovations of buildings and energy policies should prioritize skill availability. Smart subsidy schemes and information access can encourage combined renovation works and clean energy installations.
- **Cross-Border Recognition of Skills:** Mutual recognition of qualifications and the development of an EU-wide certification standard for electricians should be pursued under the Services Directive and the Renewable Energy Directive. Authorities should accelerate these procedures.
- **Integration of Solar Sector Needs into Immigration Policies:** The EU should facilitate the entry of workers from third countries to support the growth of the solar sector, aligning with strategic priorities. Talent Partnerships and the EU Talent Pool can play a role in this process. Solar PV, as a vital sector for Europe's challenges, should be central to these mechanisms.

KPIs

KPI	Target value 2035
Number of Skilled Workers in the Solar Industry	Sufficient workforce to meet industry growth and expansion needs. Enhance re-skilling and up-skilling programs, improve STEM education, and promote careers in the solar sector.
Cross-Border Recognition of Qualifications	100% mutual recognition of solar energy-related qualifications across all EU member states. Develop and implement an EU-wide certification standard, streamline recognition processes, and promote regulatory alignment.

7.2.2
Roadmap 6: Gender Equality

Rationale for support

Gender equality in the solar PV sector is crucial for fostering a diverse and inclusive workforce that can effectively meet the industry's growth demands. Despite comprising 40% of the full-time workforce, women are significantly underrepresented in technical and leadership roles. This underrepresentation not only limits women's career advancement but also hampers the sector's overall innovation and productivity potential. Addressing gender disparities is essential not only from a social justice perspective but also to harness the talents and perspectives of a broader pool of skilled professionals.

Status

Referring to the 2022 IRENA gender perspective report[113], women in the solar PV industry face persistent barriers to entry and career advancement. They are disproportionately represented in administrative roles (58%) compared to technical roles like manufacturing (47%) and installers (12%). Moreover, women hold only 32% of STEM positions and a mere 13% of senior management roles. These figures underscore the need for targeted interventions to promote gender parity across all levels of the solar PV workforce.

Types of activities/targets

- **Awareness and Cultural Change:** Initiatives should focus on raising awareness about gender biases and stereotypes within the industry. Educational campaigns and open discussions can challenge existing norms and promote inclusivity. By fostering a culture that values diversity, the sector can attract and retain more women professionals.
- **Policy Improvements:** National policies must evolve to enforce equal opportunity practices and eliminate gender-based discrimination. This includes revising hiring and promotion processes to ensure transparency and meritocracy, which are crucial for advancing women's careers in STEM and leadership roles within the PV sector.
- **Workplace Practices:** Companies should implement fair workplace practices that support work-life balance, such as maternity and paternity leave, flexible work arrangements, and improved facilities. These measures not only support gender equality but also enhance overall employee satisfaction and productivity.
- **Support Networks and Mentorship:** Establishing mentorship programs and support networks can provide crucial guidance and encouragement for women in the PV industry. These programs help mitigate the challenges women face in a predominantly male-dominated field and facilitate career progression through networking opportunities and skill development.

[113] *Solar PV: A Gender Perspective (irena.org)*

7.3
Objective 3: Environmental and Social Sustainability

Integrating environmental and social dimensions into the PV sector is crucial for an inclusive, equitable and sustainable energy transition. The Environmental, Social, and Governance (ESG) framework plays a key role in promoting sustainable practices within the solar PV industry. However, challenges remain due to data gaps and supply chain transparency. Our proposed solutions include improving data accessibility, enhancing supply chain transparency, and implementing comprehensive methodologies to promote environmental and social sustainability of the PV sector along the whole life cycle, from the critical raw material extraction to the waste management and PV plants decommissioning.

7.3.1
Roadmap 7: Social Impact Assessment and S-LCA

Rationale for support

The integration of social dimensions into the PV sector is critical for ensuring that the sustainable energy transition is inclusive, equitable, and beneficial to all stakeholders. As PV systems are socio-technological systems, their impact extends beyond physical components to encompass the people who design, implement, manage, and use these technologies. Investigating and addressing the social impacts of PV technologies along their entire value chain is essential for fostering social innovation, equitable business models, and effective policies that support sustainable development[114].

Status

Currently, the social impacts of PV systems are not comprehensively assessed, primarily due to the complexity of capturing social data and the lack of standardized methodologies like Social Life Cycle Assessment (S-LCA). While efforts have been made to formalize S-LCA, such as UNEP's guidelines for social life cycle assement for products,[115] challenges remain in data collection, local specificity, and dissemination of results. Additionally, the EU's recent Forced Labor Ban and the need for better regulation of PV waste management highlight the necessity of addressing social impacts across the PV supply chain, including working conditions and end-of-life processes[116].

Types of activities/targets

- **Develop Comprehensive Database:** Comprehensive databases to support the Social Life Cycle Assessment (S-LCA) approach, addressing the high data requirements and overcoming the challenges posed by the current lack of foundational databases, data subjectivity, and privacy constraints.
- **Enhance Local Data Collection:** Strategies to collect specific local data with high resolution, ensuring that local conditions and context are accurately represented in S-LCA studies.
- **Standardise and Internationalise S-LCA:** Standardised and internationally recognized guidelines and methodologies for S-LCA to facilitate consistent, understandable, and comparable results.

[114] *DOI: 10.1080/09505431.2013.786989*
[115] *Guidelines for social life cycle assessment of products | UNEP - UN Environment Programme*
[116] *https://www.europarl.europa.eu/news/en/press-room/20240419IPR20551/products-made-with-forced-labour-to-be-banned-from-eu-single-market*

- **Improve Data Accessibility and Transparency:** Data accessibility and transparency while respecting privacy conditions to ensure the full contribution of necessary information for S-LCA.
- **Promote Understanding and Dissemination of S-LCA Results:** Understanding and dissemination of S-LCA results, making them accessible and comprehensible to a broader audience, including stakeholders and decision-makers.

KPIs

KPI	Target value 2035
Number of jobs created in the local community as a result of PV manufacturing.	Increase of PV related jobs in Europe, from 3% of 2023.
Methodology definition for the social screening of the PV suppliers	Selection and definition of a set of indicators that are relevant for the S-LCA of the PV supply chain, from raw materials extraction to final product. With definition of specific measurement methods and units of measurement for each indicator (e.g., fair wage, fair working hours, freedom of association)
Methodology definition for the social screening of the PV waste management	Selection and definition of a set of indicators that are relevant for the S-LCA of the PV waste management operations. With definition of specific measurement methods and units of measurement for each indicator. (e.g., exposure to toxic chemicals, fair working conditions)

7.3.2
Roadmap 8: Environmental, Social and Governance (ESG) framework

Rationale for support

The Environmental, Social, and Governance (ESG) framework is critical for promoting sustainable practices in the solar PV sector, ensuring long-term value creation and risk mitigation for investors and developers. By integrating ESG principles, the solar PV industry can align with the EU's Net Zero Initiative and the European Green Deal, fostering ethical and sustainable growth. Emphasizing ESG criteria helps companies focus on long-term value rather than short-term profitability, addressing ethical concerns and supporting the global movement towards sustainability.

Status

Currently, the solar PV industry faces challenges in integrating comprehensive ESG practices due to a lack of standardised information and transparent supply chains. Issues such as the ethical sourcing of critical raw materials, biodiversity impacts, and waste management are often not fully addressed. The industry needs clear guidelines and robust verification processes to enhance ESG compliance and investor confidence.

Types of activities/targets

- **Award Criteria for Low Carbon Footprint:** Establish procurement criteria favoring PV modules with low carbon footprints, ISO 14001 certification, and independently issued LCA studies. Promote PV modules that use minimal critical raw materials and are designed for recyclability.
- **Decommissioning and Repowering Plans:** Require engineering procurement and construction (EPC) and operations & maintenance (O&M) companies to provide clear decommissioning or repowering plans that include repurposing, recycling, and refurbishing PV modules according to ISO 2859 AQL standards.
- **Biodiversity Guidelines:** Implement guidelines to increase biodiversity in PV projects, using certifications like TNO eco-certified parks or Kiwa Nature Inclusive Solar Parks, and adhere to Solar Power Europe's best practices for integrating biodiversity.
- Supply Chain Transparency: Address forced labor concerns by enhancing supply chain transparency and responsible production practices. Mitigate risks beyond suppliers' codes of conduct and comply with EU regulations to exclude forced labor products from the market.
- Third-Party Verification: Promote independent third-party verification of ESG practices in the supply chain through schemes like SolarPower Europe's Solar Stewardship initiative. Ensure robust verification processes involving quality assurance companies.

KPIs

KPI	Estimated Target value 2035
Environmental: insights into the carbon footprint, energy yield, resource & land use efficiency, biodiversity, water usage and waste management are mapped	Companies and organisations evaluate and align with EU requirements which is contractually agreed upon, monitored, and annually reported.
Social: number of jobs, records of incidents, community engagement initiatives, training & development of community and team, contributions to local social projects or infrastructure.	Companies and organisations evaluate and align with EU requirements which is contractually agreed upon, monitored, and annually reported.
Governance: how the project is adhering to local regulatory demands & updates thereof, level of transparency of all ESG criteria, how Diversity Equity and Inclusion are integrated, what anti-corruption/whislteblowing policies there are and supply chain transparency with matching factory audits and know your counter party due diligences of all stakeholders.	Companies and organisations evaluate and align with EU requirements which is contractually agreed upon, monitored, and annually reported.

[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.*

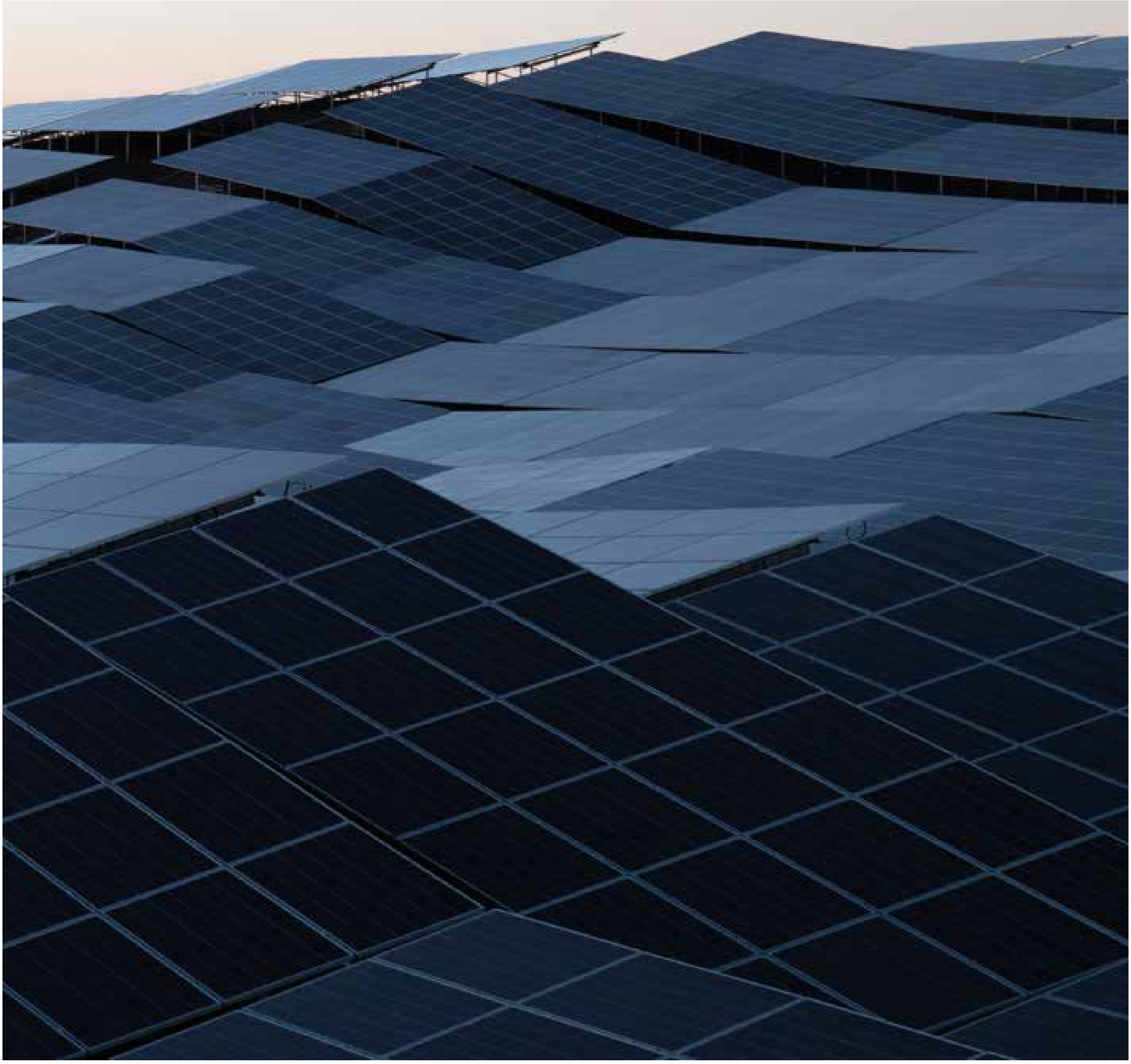
[ii] *Bogdanov et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy, 227, 120467 (2021), see https://doi.org/10.1016/j.energy.2021.120467*

[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-REmaptransition-pathway.*

[vi] *Sky Scenario, see Sky scenario | Shell Global.*



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