EUROPEAN
COMMISSION

Brussels, 24.6.2024
SWD(2024) 160 final

COMMISSION STAFF WORKING DOCUMENT

Solar energy joint research and innovation agenda with Member States in the context of the European Research Area (ERA)

1. INTRODUCTION

Solar energy technologies provide the means to utilise the energy of the sunlight that strikes the earth's surface by converting it either into electricity in the case of solar photovoltaics (solar PV), or into heat and then electricity in the case of concentrated solar power (CSP), or into heat in the case of concentrated and non-concentrated solar thermal technologies.

Solar energy is cheap, clean and flexible. The solar energy sector has become a very dynamic and competitive industry, ensuring a constant output of innovative technologies. The EU has one of the strongest innovation environments across all solar energy technologies, from PV to CSP. The cost of solar power decreased by 82% between 2010-2020 ([1]), making it the most accessible renewable energy for households, contributing to protecting consumers from volatile energy prices. In addition, its accelerated deployment contributes to reducing the EU's dependence on imported fossil fuels.

The EU has since long been a frontrunner in the development and deployment of solar energy. The **European Green Deal**, its **Industrial Plan** ([2]) and the **REPowerEU Plan** ([3]) have turned solar energy into a building block of the EU's transition towards a net-zero economy. As part of the REPowerEU Plan, the Commission adopted in May 2022 an **EU Solar Energy Strategy** ([4]), which aims to install over 320 GW of solar PV by 2025 and almost 600 GW by 2030. This strategy recognises the important role of R&I on the one hand to reduce the cost of existing solar energy technologies while increasing their energy conversion efficiency, and on the other hand to support new technologies, environmental and socio-economic sustainability including in the manufacturing phase, and integrated designs. Furthermore, continued investments in R&I are needed to support the societal dimension of the solar energy transition and increase resilience and efficiency of solar energy systems under changing climate conditions.

To keep pace with the increasing demand of solar technologies, especially solar PV, and to avoid creating new dependencies threatening our effort to climate neutrality by 2050, the EU needs to build a strong clean energy manufacturing sector and supply chain that produce cost-competitive clean energy products. The 2023 **Green Deal Industrial Plan** ([5]) aims to enhance the competitiveness of Europe's net-zero industry and support the fast transition to climate neutrality. As part of this Plan, the Commission has put forward a **Critical Raw Materials Act** ([6]) and the **Net-Zero Industry Act (NZIA)** ([7]) to underpin industrial manufacturing of key net-zero technologies in the EU, among them solar PV and solar thermal technologies.

([1]) Solar energy (europa.eu).
([2]) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, A Green Deal Industrial Plan for the Net-Zero Age, COM/2023/62.
([3]) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, REPowerEU Plan, COM/2022/230 final.
([4]) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee And The Committee of the Regions, EU Solar Energy Strategy, COM/2022/221 final.
([5]) See note 1, page 1.
([6]) Regulation of the European Parliament and of the Council, Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials, Regulation (EU) 2024/1252.
([7]) Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act), COM/2023/161 final.

Within the above framework, and as recently announced in the **European Solar Charter** ([8]), the Commission is also working to propose **Ecodesign** and **Energy Labelling** regulations for solar PV products to establish, on the basis of a robust methodology, appropriate environmental and energy performance standards for the sector. Ecodesign and energy labelling requirements would help promoting the competitiveness of environmentally sustainable PV products.

To accelerate the development and deployment of solar energy in Europe, it is crucial to join forces around a **joint research and innovation agenda with Member States**, since the technology and competitiveness challenges of the solar energy sector can only be addressed with a coordinated effort at the European level. Coordination already happens in the work of the **Strategic Energy Technology (SET) Plan** ([9]), through its implementation working group on solar PV and its implementation working group on solar thermal. The joint agenda, which is a key action of the EU Solar Energy Strategy, not only leverages the work of the SET Plan working groups, but it is also the outcome of a wider consultation that includes the Horizon Europe Cluster 5 'Climate, Energy and Mobility' Programme Committee, the ERA Forum for Transition and the Research Working Party.

The solar energy joint research and innovation agenda offers a strategic approach to advancing key technologies by 2030, thus streamlining the R&I efforts of the EU and Member States, identifying crosscutting issues and addressing the solar energy sector as a whole. This will ultimately contribute to the transition to a more sustainable energy future.

2. STATE OF SOLAR ENERGY TECHNOLOGIES

Solar PV and solar thermal technologies are identified as net-zero technologies under the Net-Zero Industry Act, which aims to increase the EU's manufacturing capacity of net-zero technologies to at least 40% of annual deployment needs by 2030.

2.1. Solar PV

Solar PV has been the fastest growing technology by capacity additions in recent years ([10]) and **provides cheaper electricity than fossil-fuel power plants** in most countries. It plays a pivotal role in all scenarios for a climate neutral energy system. In the EU, solar PV electricity generation **grew by 36 TWh in 2023**, reaching almost 9% of the EU's total electricity generation ([11]). Cumulatively, solar PV capacity now stands at 259,99 GW ([12]). The installed capacity growth for 2023 puts the EU in line with Solar Power Europe's most likely scenario ([13]) (which estimated 56 GW additions) and on track to surpass the REPowerEU **capacity goal of 320 GWac by 2025**. The EU Solar Energy Strategy aims at an **additional capacity of 600 GWac by 2030**, a four-fold increase compared to 2020 levels.

Solar PV installations rely to a very large extent on **crystalline silicon technology**, which continues to improve energy conversion efficiency and reduce material usage. European research institutes and universities have introduced many innovations for crystalline silicon PV

([8]) Commission supports European photovoltaic manufacturing sector with new European Solar Charter (europa.eu).
([9]) Strategic Energy Technology Plan (europa.eu).
([10]) Solar - IEA.
([11]) European Electricity Review 2024 | Ember (ember-climate.org).
([12]) Solar energy (europa.eu).
([13]) EU Market Outlook for Solar Power 2023-2027 - SolarPower Europe.

in the last decades, jointly with industry (manufacturers and equipment suppliers). Amongst them are **innovations for silicon** (Siemens reactors), **crystallization** (e.g., directional solidification), **wafering** (e.g., diamond wire saws), **solar cell manufacturing** (e.g., PECVD SiNx, multi texturing, AlOx for PERC cells, laser ablation) and module technology. In 2023, commercial modules using the latest device architectures offered an average efficiency of 21.1%, and a maximum of 24.7% ([14]). A Chinese PV manufacturer has set a new world record in 2023 of 27.09% for the efficiency of crystalline silicon Heterojunction Back Contact (HBC) solar cells ([15]). Innovative materials, such as perovskites, offer possibilities for further development. A perovskite/silicon tandem device set a record efficiency of 33.7% in May 2023 ([16]). Pilot lines for such tandems are in development, for instance in Germany, Sweden, Poland and France, but commercial products are not yet available ([17]). Inverters are also a vital component of the PV technology value chain, playing a crucial role in system efficiency, data protection, and cybersecurity. Given that inverters can potentially be exploited to cause blackouts, R&I in, as well as European manufacturing of inverters are essential for ensuring resilient value chains and a secure energy supply.

While EU remains a strong innovator, in 2022 over 95% of Europe's solar panels came from China ([18]). To meet Europe's renewable energy objectives, the European Commission has launched the **European Solar PV Industry Alliance** ([19]). The Alliance aims to develop an EU solar PV industrial ecosystem to help secure and diversify supplies of solar PV and thereby accelerate solar PV deployment in the EU. Its objective (considered achievable by 2030) is to scale up to 30 GW the annual solar PV manufacturing capacity in Europe, facilitating investment, de-risking sector acceleration, and supporting Europe's decarbonisation targets. The Alliance has a specific research and innovation pillar under the Horizon Europe Cluster 5 'Climate, Energy, and Mobility'. Within this pillar, a **Horizon Europe co-programmed European Partnership on solar PV** is under preparation. Its aim is to promote the industrial engagement in PV R&I and support the innovation ecosystem across the full value chain, fostering the uptake of R&I results for the manufacturing of novel and enhanced technologies in Europe. However, there is **stiff international competition to attract manufacturing investments**. The United States for example included generous new funding for solar PV in the **Inflation Reduction Act (IRA)** introduced in 2022 ([20]) and an increase from 25% to 50% in the tariff rate on solar cells (whether or not assembled into modules) in 2024 ([21]). Investment and production tax credits are expected to give a significant boost to solar PV capacity and supply chain expansion in the United States.

Energy technologies, including solar PV, are included in **the list of ten critical technology areas for the EU's economic security** ([22]). To mitigate risks such as supply chain dependencies or technology leakage, the Commission and the Member States are carrying out a collective

([14]) Solar cell efficiency tables (Version 63).
([15]) Longi - New silicon solar cell efficiency record (pveurope.eu).
([16]) NREL, Best research-cell efficiency chart, Photovoltaic Research.
([17]) Progress on competitiveness of clean energy technologies.
([18]) International trade in products related to green energy - Statistics Explained (europa.eu).
([19]) Home - European Solar PV Industry Alliance (solaralliance.eu).
([20]) Inflation Reduction Act.
([21]) FACT SHEET: President Biden Takes Action to Protect American Workers and Businesses from China's Unfair Trade Practices | The White House.
([22]) Annex to the Commission Recommendation on critical technology areas for the EU's economic security for further risk assessment with Member States, C(2023) 6689 final.

risk assessment exercise to identify and analyse vulnerabilities of systemic nature which may affect negatively the EU's economic security. The outcome of the risk assessments, when finalised, could inform precise and proportionate measures to implement the European economic security strategy, including measures to promote EU competitiveness, enhance research security and strengthen international partnerships.

2.2. Solar thermal

The demand to develop new and improved ways to heat and cool homes, cities and industries in a sustainable way is increasing and solar thermal technologies play a key role. Furthermore, CSP can significantly contribute to the transformation of the European energy system by providing dispatchable electricity, that can complement the integration of variable output renewables such as solar PV or wind energy, supporting the reliable operation of the transmission grid. Thermal energy storage is a key feature of all solar thermal energy technologies.

CSP can substantially contribute to electricity generation in locations with high direct insolation, but only a fraction of its potential has been harnessed so far ([23]). In 2022, worldwide installed capacity was approximately 6.4 GW, with 2.3 GW installed in the EU ([24]) (the EU installed capacity is almost completely located in Spain). CSP has shown considerable progress in terms of cost reduction and between 2010-2022 the global average cost of new CSP projects saw approximately a 69% decrease. The capacity factor has also significantly improved thanks to more cost-effective thermal energy storage systems. European organizations play a leading role in research and technological development and EU researchers are top publishers of scientific papers and authors of high-value patents.

Non-concentrated and **concentrated solar thermal** technologies **collect the thermal energy** of the sun and use the heat to provide diverse energy supplies such as **hot water, process heat, space heating and space cooling.** These systems serve millions of residential, commercial, and industrial applications in the EU and worldwide with an ample variety of technologies ([25]). Since 2010, installation costs have decreased substantially, in particular for solar district heating and for solar industrial heat.

Non-concentrated solar thermal technologies are considered mature, but there is still large room for performance increase ([26]). **90% of the non-concentrated solar thermal equipment demand in Europe is supplied by European manufacturers** that produce diverse components (e.g., solar collectors, storage tanks, expansion vessels). Manufacturing can be ramped up quickly, but new developments are still needed (for example in terms of novel components and innovative ways of system integration).

CSP technologies have so far been used primarily in large power plants and it was thanks to EU and national support for research activities that new interest grew for this technology. **The first CSP plant with thermal energy storage worldwide was supported by an EU**

([23]) SolarPACES - International CSP research.
([24]) Concentrated solar power and solar heating and cooling in the European Union (europa.eu).
([25]) IEA SHC || Solar Heat Worldwide (iea-shc.org).
([26]) IEA SHC || Projects (iea-shc.org).

demonstration project ([27]) and all subsequent plants apply a similar design. Furthermore, the current molten salt tower technologies are the outcome of EU funded research.

Notable examples of R&I achievements in solar thermal are the EU-funded project SOLARBREW ([28]), which achieved a 19% solar fraction of heat in industrial brewing processes, while the project SUN-TO-LIQUID ([29]) reached a record solar-to-syngas conversion efficiency of > 5%, with subsequent transformation to kerosene.

Horizon Europe funding supports the development of several solutions, such as solar-driven gas turbines, innovative thermal energy storage systems, the integration of solar heat in industrial processes, novel solar collectors, and the use of supercritical CO_2 cycles for concentrated solar thermal plants.

3. FUNDING OPPORTUNITIES AND PRIVATE INVESTMENTS IN SOLAR ENERGY R&I IN EUROPE

With the recent **Communication** ([30]) **on a 2040 climate target**, recommending net greenhouse gas emissions reduction of 90% by 2040 compared to 1990 levels, the EU sets a firm pace to climate neutrality by 2050, and provides **certainty and predictability** for investment decisions in clean energy technologies.

Europe offers numerous investment opportunities in solar energy R&I. The EU and national governments have implemented several funding programmes. These investments aim to drive **technological advancements**, **improve energy efficiency**, and **accelerate the transition towards sustainable and clean energy sources.**

EU R&I support is provided in multiple ways, through for example:

- **Horizon Europe (Pillar II clusters)** ([31]): The EU's Framework Programme for Research and Innovation, Horizon Europe, provides significant funding opportunities for solar energy R&I. It supports research projects, collaborative partnerships, and innovation activities in various areas, including solar technologies and their integration in low-carbon energy systems. For instance, the parts of the Horizon Europe Work Programmes on Cluster 5 ‘Climate, Energy and Mobility’ for the period 2021-2022 and 2023-2024 have invested until now through the destination ‘Sustainable, secure and competitive energy supply’ almost EUR 370 M in solar technologies (PV, CSP and solar thermal technologies).
- **European Innovation Council (EIC)** ([32]): As part of Pillar III ‘Innovative Europe’ of Horizon Europe, the EIC offers financial support to innovative companies and entrepreneurs across Europe. It provides grants, equity investments, and other forms of

---

([27]) Andasol 50MWe Eurotrough solar thermal plant with thermal storage in the Marquesado Valley (Granada, Spain) | ANDASOL | Project | Fact sheet | FP5 | CORDIS | European Commission (europa.eu).
([28]) Solar Brewing the Future | SOLARBREW | Project | Fact sheet | FP7 | CORDIS | European Commission (europa.eu).
([29]) SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels | SUN-to-LIQUID | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu).
([30]) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society, COM/2024/63 final.
([31]) Horizon Europe - European Commission (europa.eu).
([32]) European Innovation Council - European Commission (europa.eu).

financial assistance to scale up and commercialize breakthrough technologies, including solar energy innovations. For the period 2021-2023 the EIC granted around EUR 31 M on projects in solar PV.

- **Innovation Fund** ([33]), financed by EU Emissions Trading System revenues ([34]), is one of the world's largest funding programmes for the deployment of net-zero and innovative technologies. The Fund focuses on supporting innovative clean technologies and big flagship projects with European added value that can bring significant emission and greenhouse gas reductions. The Innovation Fund through the call for grants held over the period 2021-2023 is supporting 11 solar projects with an EU contribution of almost EUR 430 M.
- The **European Institute of Innovation and Technology (EIT)** ([35]), a body created under the third pillar of Horizon Europe, has established the Knowledge and Innovation Community 'InnoEnergy'. InnoEnergy is driving forward industrial value chains in three strategic sectors, including battery storage, green hydrogen as well as solar photovoltaics through the European Solar PV Industry Alliance (ESIA) ([36]).
- **European Structural and Investment Funds (ESIF)** ([37]): These funds, such as the European Regional Development Fund and the Cohesion Fund, promote regional development and innovation and can be utilized by Member States to support R&I projects in renewable energy, including solar energy.

At national level, similarly, there are many examples, such as:

- **Austria:** The Federal Climate Protection Ministry (BMK) and the Climate and Energy Fund have initiatives to foster a sustainable energy system. Through funding programs for research, development, and market penetration, the aim is to advance research on new, climate-friendly energy technologies and cultivate an innovation hub for next-generation energy technologies.
- **Denmark:** Every year, the Energy Technology Development and Demonstration Programme led by the Danish Energy Agency funds work by enterprises and universities on demonstration of new efficient and climate-friendly energy technologies that can help Denmark become free of fossil fuels by 2050. A special fund is allocated for activities on solar technologies.
- **Estonia:** The Environmental Investments Centre provides funds from the state budget (including revenue from environmental charges, EU funds, funds from foreign aid programs as well as the Green Investment Scheme) for the implementation of environmental projects.
- **France:** The French National Research Agency (ANR) and the French Environment and Energy Management Agency (ADEME) provide funding for solar energy R&I projects through various programmes, such as the Investments for the Future initiative.
- **Germany:** The Energy Research Programme drives the development of new climate-friendly generations of technology. In 2022, the Federal Ministry for Economic Affairs and Climate Protection (BMWK) approved 105 new solar PV funded projects based on

([33]) Innovation Fund - European Commission (europa.eu).
([34]) Directive of the European Parliament and of the Council, Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community, Directive 2003/87/EC.
([35]) European Institute of Innovation & Technology (EIT) | EIT (europa.eu).
([36]) EIT InnoEnergy- Accelerating sustainable energy innovations.
([37]) Inforegio - Available budget of Cohesion Policy 2021-2027 (europa.eu).

the 7th Energy Research Programme. Around EUR 69 M were invested in research and development projects. The next, 8^{th} Energy Research Programme is currently under preparation and will launch five research missions (Energy System, Heat Transition, Electricity Transition, Hydrogen, and Transfer) that set concrete, ambitious goals for the contribution of applied energy research to the transformation of the energy system. Various solar PV technological aspects of this document are considered within the 8^{th} Energy Research Programme.

- **Greece:** The Centre for Renewable Energy Sources and Saving (CRES) represents the Greek national institution for the funding of renewable energy sources, including solar PV and solar thermal.
- **Italy:** The Energy Technologies and Renewable Energy Sources Department (TERIN) of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) conducts research and fosters activities in the field of renewable energy sources, such as solar thermal and solar PV energy. Furthermore, the support for scientific research in this field is strengthened through the National Research Programme (NRP) and Research Projects of Significant National Interest (PRIN).
- **Netherlands:** SolarNL is a national research, innovation and industrial investment programme to advance solar PV systems in the Netherlands and Europe. The programme is subsidized by the National Growth Fund (Nationaal Groeifonds), which formally started in 2024.
- **Poland:** The National Centre for Research and Development (NCBR) runs a strategic programme ‘New technologies in the field of energy (NTE)’ aimed at increasing the potential of the renewable energy industry including in the area of solar energy. The National Science Centre (NCN) supports basic research across all science fields from national funds.
- **Slovakia:** The Slovak Renewable Energy Agency supports applied research and development in the field of solar energy use.
- **Spain:** The Institute for Energy Diversification and Savings (IDAE), promotes measures and projects for deployment related to energy efficiency and renewable energy. In doing so, IDAE is involved in the financing of projects and the development and management of public assistance programmes that target the main energy-consuming sectors. The Ministry of Science, Innovation and Universities, through its two national funding agencies (CDTI and SRA) provides also different R&I funding programmes covering, among all, renewable energy technologies, including solar energy.
- **Sweden:** The Swedish Energy Agency contributes to the development of new technologies that focus on the increased use of renewable energy sources.

The EU's SET Plan is an example of coordination and collaboration in clean energy R&I of European and national efforts (of the SET Plan countries) for the development of clean, efficient and cost-competitive energy technologies. Through 14 implementation working groups (IWGs), the SET Plan activities have focused on the six priorities of the Research, Innovation and Competitiveness dimension of the Energy Union. Under the SET Plan Priority

"Becoming world number one in renewables", the **IWG on PV** ([38]) and the **IWG on CST** ([39]) have set technological R&I priorities with challenging objectives.

The creation of the **European Clean Energy Transition Partnership** ([40]) under Horizon Europe is an example of successful cross-sectoral cooperation through the SET Plan. This **joint activity** with Member States is complementary with the activities funded by the Horizon Europe programme in the clean energy domain.

Private investments in solar energy R&I across Europe can vary significantly based on market conditions, technological advancements, and policy frameworks. Private investors, venture capital firms and companies interested in the renewable energy sector support solar energy R&I through equity investments, project financing, and partnerships. These investments typically target innovative solar technologies, manufacturing processes, materials research, and business models that enhance solar energy generation, storage, and system integration.

Overall, the combination of EU and national R&I funding opportunities, along with private investments, contribute to the advancement of solar energy R&I in Europe and accelerate the transition to a sustainable energy future.

4. Technological R&I priorities of the SET Plan for solar PV

Solar PV has already proven to be economically and environmentally competitive, though to become a major player of the clean energy system it must successfully address further challenges related to device innovation, manufacturing, integration and circularity, illustrated in the following.

Massive rollout and integration of solar energy at affordable cost, in an environmentally and societally sustainable way: The massive rollout of solar PV, which contributes to the EU 2050 climate neutrality goal, requires addressing a range of challenges at the same time:

a) Further reduce the solar PV generation cost. Reductions here will offset increases in energy system costs due to grid extension, batteries, or other storage technologies.
b) Make solar PV readily available for a range of various applications. Solar PV not just as a standardised 'add on' module, which helped to make the technology affordable, but increasingly also as an integrated multipurpose solution, for instance in electricity-generating buildings, car roofs, and many other surfaces; or as solar PV systems integrated into infrastructure (e.g., roads, noise barriers, dikes), solar PV in combination with agriculture (agriPV) or water basins (floating PV) and in combination with land or water management to avoid further biodiversity impact.

Supporting Economic Recovery and Building the Value Chains for Renewables: The solar PV industry has changed radically in recent years. In Europe, the rapid growth of the solar PV market has not led to similar growth in manufacturing capacity as policies have focused on supporting generation and use. As a result, Europe has lost considerable industrial market share over the last 10 to 15 years. Recent rapid cost reductions in setting up solar PV manufacturing capacity, coupled with a large increase in demand for the various forms solar PV can take, should trigger 'made in Europe PV'. Capital expenditure costs for polysilicon, wafer, solar cell

---

([38]) Home - IWG-PV.eu.
([39]) Concentrated Solar Thermal Technologies - European Commission (europa.eu).
([40]) Clean Energy Transition Partnership (cetpartnership.eu).

and module manufacturing have decreased by 75 to 90% between 2010 and 2020 ([41]). Economies of scale manufacturing are critical, and a recent study has shown that a European value chain would be competitive with huge solar PV factories, each with an annual production volume between 5 and 10 GW ([42]).

Using Circularity to Ensure a Sustainable Transition: Embracing the principle of a circular economy, the solar PV sector will need to achieve circularity while maintaining the already proven strengths in terms of cost, performance, and reliability. Providing the best solutions that take these requirements into account is an opportunity for the European solar PV sector to build up new manufacturing capacity.

As R&I needs to cover these challenges, the following priorities have been derived within the SET Plan **PV Implementation Plan of PV IWG** ([43]):

Research area: performance enhancement and cost reduction through advanced solar PV technologies and manufacturing

Priority PV.1: PV modules with higher efficiencies and lower costs

This priority focuses on **improving efficiency and reducing costs of PV modules**. It covers the **various solar PV technologies** that have already reached industrial maturity level as well as emerging technologies.

Priority PV.2: System design for lower LCoE of various applications

This priority focuses on R&D needs **beyond the PV module**, and on improving the energy yield of systems. For the past decades, the focus of cost reduction and efficiency improvements has mostly been on PV modules, as they have traditionally been the costliest component of a solar PV system. With the strong reduction of their prices, the modules still remain the most important cost component of a solar PV system, but the impact on the levelized cost of electricity (LCoE) of other parts of the value chain becomes increasingly important. The priority may include as well, the combination of PV and CSP systems.

Priority PV.3: Digitalisation of PV

The digital transition presents key opportunities for the solar PV sector: not only can new digital technologies allow for the emergence of new solar PV business models and for the improvement of existing models, but they can also be used to reduce costs and increase performance at almost every point of the value chain.

Research area: lifetime, reliability and sustainability enhancements (through advanced PV technologies, manufacturing and applications)

([41]) Commission Staff Working Document, Clean Energy Transition – Technologies and Innovations Accompanying the document Report from the Commission to the European Parliament and the Council on progress of clean energy competitiveness, SWD/2020/953 final.
([42]) Rebuilding Europe's solar supply chain | McKinsey.
([43]) SET Plan TWP PV Implementation Plan, Final Draft 2023.

Priority PV.4: Sustainable and circular solar PV

This objective focuses on reducing solar PV's environmental footprint, across the entire value chain (production, transport, installation, operation and end-of-life of solar PV systems).

Priority PV.5: Reliable and bankable solar PV

The most effective strategy for reliable and bankable solar PV is to reduce the risk for operational failures, **prevent their occurrence** and, in case they occur, reduce their impact on LCoE. A standardised **yield assessment** with reduced uncertainties can contribute to de-risking the investment and create a more favourable business case. **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.

Research area: new applications through integration of photovoltaics (for diversified and dual-purpose deployment and enhanced value)

Priority PV.6: Physical integration of solar PV into the built environment, vehicles, landscapes & infrastructures

The inherent **modularity** of PV enables it to be **integrated seamlessly into many different objects**, allowing space to be used efficiently. PV-enabled products must meet the requirements of the original product. As most of the integrated PV value chains are in Europe, this creates **huge opportunities for European value and job creation**.

Research area: smart energy system integration of photovoltaics (for large scale deployment and high penetration)

Priority PV.7: Energy system integration

Solar PV is growing strong in independent applications at all levels, on roofs or facades of buildings for both domestic and commercial use, as well as in commercial systems of various sizes. In the years to come, solar **PV should be looked at as active contributor of the integrated grid** utilising dependable forecasting tools for improving the reliability of the complete system.

Research area: socio-economic aspects of the transition to high PV contribution

Priority PV.8: Higher awareness of solar PV-related externalities and benefits

Facing the need to increase renewable electricity generation to meet the goals of the Green Deal and the Paris Agreement, it is a logical step to **involve people/society** to utilise solar PV technology on a wider scale, especially in urban and highly dense spaces throughout Europe.

Table 1. Solar PV research areas, priorities and activities

	Performance enhancement and cost reduction through advanced solar PV technologies and manufacturing
Priorities	**Activities**
PV.1: PV modules with higher efficiencies and lower costs	**PV.1.1 | Silicon PV modules** There is potential for further innovation in performance, integration and sustainability enabling large-scale deployment, while decreasing production cost. **PV.1.2 | Perovskite PV modules** The long-term vision is that they will be produced at very low costs, be highly efficient and stable and represent a broad scope of embodiments (e.g., flexible, rigid, opaque, semi-transparent). **PV.1.3 | Thin-film (non-perovskite) PV modules** Module efficiencies should be comparable to current PV technologies within five years. Manufacturing should quickly achieve comparable costs to currently commercial technologies. **PV.1.4 | Tandem PV modules** For 2030, these should reach a market share of more than 5% and should successfully transition to mass market applications, while demonstrating long-term performance comparable to the single-junction technologies and clear advantages in terms of LCoE and environmental footprint.
PV.2: System design for lower LCoE of various applications	**PV.2.1 | Balance of System (BoS) and energy yield improvement** Focusing R&I on other components (e.g., inverters or power electronics) and activities such as installation, operation, maintenance, decommissioning.
PV.3: Digitalisation of solar PV	**PV.3.1 | Digitalisation of PV manufacturing** Introducing digital technologies to reduce cost and increase the quality of PV value chain manufacturing. **PV.3.2 | Digitalisation of solar PV systems** Introducing digital technologies to increase energy yield, and to make solar PV technology suited for all emerging new applications and a dependable component of the energy system of the future.
	Lifetime, reliability and sustainability enhancements (through advanced PV technologies, manufacturing and applications)
PV.4: Sustainable and circular solar PV	**PV.4.1 | Refuse, Rethink and Reduce (Low environmental impact materials, products, and processes)** Optimising consumption of resources, materials, energy demand and carbon emissions of solar PV technologies over the entire value chain.

	PV.4.2 | Reuse, Repair and Refurbish (Designs, systems and O&M for reuse) Extending PV device useful lifetime and diverting PV 'waste' from the recycling path. **PV.4.3 | Recycle and recover** Improving the recycling and upcycling process of PV modules. **PV.4.4 | Technologies for sustainable manufacturing** Investigating ways of reducing both the energy and greenhouse gas emissions in solar PV production. **PV.4.5 | Eco-labelling and energy-labelling** Focusing on accurate, and up-to-date, life cycle inventory databases, including the Eco-Invent Database, GABI database and the European Commission Life Cycle data information system.
PV.5: Reliable and bankable solar PV	**PV.5.1 | Quality assurance to increase lifetime and reliability** Improving and standardising quality assurance and quality control methodologies and techniques to provide a more accurate evaluation of lifetime and reliability of PV products. **PV.5.2 | Increased field performance and reliability** Novel technologies make the increased reliability and field performance a continuous industry demand. Solutions available on the market will need to be updated to capture innovation trends. **PV.5.3 | Bankability, warranty, and contractual terms** Creating standardised 'thresholds' for quality and performance features for bankable solar PV plants.
	New applications through integration of photovoltaics (for diversified and dual-purpose deployment and enhanced value)
PV.6: Physical integration of solar PV into the built environment, vehicles, landscapes & infrastructures	**PV.6.1 | PV integration in buildings** Zero-emission buildings are promoted as a decarbonisation solution by regulators and require the integration of renewable energy systems. Integrated PV systems in ports and airports (serving also as auxiliary power units for planes and vessels) can contribute towards the decarbonization of the sector and improve local air quality. **PV.6.2 | Vehicle Integrated PV** VIPV enables the electrification of the transport system by converting solar energy directly on the vehicle. PV-powered applications such as PV-powered vehicles, PV equipped electricity supply equipment and integrated electrical systems consisting of PV-powered vehicles including cars and trucks can contribute greatly to the decarbonization of the road transport sector. **PV.6.3 | Agrivoltaics and landscape integration** Agrivoltaics allow for the combined use of land for both agricultural and solar PV use, while supporting the decarbonisation of the sector. **PV.6.4 | Floating PV** EU has 20,000 square kilometres of manmade reservoirs, on which 200 GWp of solar 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. Floating solar PV on dams for hydropower or in conjunction with wind energy induces synergies in the energy system. **PV.6.5 | Infrastructure Integrated PV** Solar PV can be integrated into infrastructural objects such as road pavement, noise barriers, crash barriers, dikes, landfills, flyovers and road roofing. **PV.6.6 | "Low-power" energy harvesting PV** Photovoltaic energy harvested in low light conditions or artificial light can be used to energize sensors, internet-of-things devices and other electronics.
	Smart energy system integration of photovoltaics (for large-scale deployment and high penetration)
PV.7: Energy system integration	**PV.7.1 | More intelligence in distributed control** This activity aims to increase the intelligence to the solar PV systems to be responsive to system needs and integrate functionalities that can contribute to the good functioning of the electricity grid. **PV.7.2 | Improved efficiencies by integration of PV-systems in DC-networks** The objective of this activity is to develop systems and solutions for which solar PV is directly connected to DC driven systems to achieve improved energy yields. **PV.7.3 | Hybrid systems including demand flexibility (solar PV + wind energy + hydropower with embedded storage + batteries + green hydrogen/fuel cells or gas turbines)** The objective of this activity is to develop systems and solutions for which solar PV, as an integral contributor of interconnected systems, can offer hybrid solutions that better meet the needs of the integrated grid. **PV.7.4 | Aggregated energy and virtual power plants (VPPs)** The objective of this activity is to develop systems and solutions for which solar PV as an integral contributor of distributed generation can be pivotal in building functional energy communities aggregated and operated through advanced distributed controls in hierarchical set up with the integrated grid. **PV.7.5 | Interoperability in communication and operation of RES smart grids** 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 solar PV components. Current issues include the lack in the harmonization of solar PV plant control and the use of proprietary solutions for monitoring and cybersecurity.
	Socio-economic aspects of the transition to high PV contribution
PV.8: Higher awareness of solar PV-related	**PV.8.1 | Wide societal involvement and participation for solar PV deployment** Solar PV can be employed by everyone. Facing the need to

externalities and benefits	increase renewable electricity generation to meet the goals of the Green Deal and the Paris Agreement, it is a logical step to involve people/society to utilise solar PV on a wider scale. **PV.8.2	Developing a PV hotbed for urban implementation** Solar PV is the only renewable energy technology that can enable renewable electricity generation in urban and highly dense spaces throughout Europe. Cities and urban regions will be one of the major boosters to increase the implementation of solar PV within the current decade.

5. TECHNOLOGICAL R&I PRIORITIES OF THE SET PLAN FOR SOLAR THERMAL

A key aspect of solar thermal technologies is that they can supply the three energy carriers: electricity, heat, and fuels. Industrial heat and fuels can be the basis for a substantial contribution of these technologies to the decarbonization efforts of industrial processes and transport. A larger integration of solar thermal technologies in the energy system will have to rely on innovative solutions that can have an impact in a variety of sectors with a view to reaching climate neutrality by 2050.

There are several challenges for solar thermal technologies, such as cost reduction, reliable thermal energy storage, improved manufacturing, integration in buildings, district systems, and industrial processes. To address these challenges, the following R&I priorities have been identified for concentrated and non-concentrated solar thermal technologies.

Research area: concentrated solar thermal technologies

The R&I priorities for concentrated solar thermal technologies are defined in the SET Plan implementation plan of CST IWG ([44]). Compared to the initial phase of the SET Plan, the focus now is not only on power production but also on other applications such as industrial process heat and solar fuels. The main technological areas are illustrated in the following.

Priority ST.1: Line-focus solar power plant technologies

Line-focus technologies are the most developed at a commercial scale as the shorter focal length makes them more attractive for sunny places with a certain level of atmospheric attenuation. The use of working fluids thermally stable at temperatures higher than 425°C would increase the power block efficiency.

Priority ST.2: Central receiver power plant technologies

The tower technology has higher efficiencies than the line-focus technology due to its higher working temperatures and thermodynamic cycle efficiencies. At present, the most

([44]) Initiative for Global Leadership in Concentrated Solar Thermal Technologies (europa.eu).

mature technology for commercial plants is based on molten-salt receivers. These systems need further advancement in cost reduction and in terms of competitiveness.

Priority ST.3: Medium and high-temperature thermal energy storage

Dispatchability is the main benefit of solar thermal electricity. This dispatchability is provided by thermal energy storage systems. The working temperature of the storage systems commercially implemented at present is either 390°C or 565°C, depending on the storage media (diathermic oils or molten salts).

Priority ST.4: Turbomachinery

Turbomachinery is to be developed for specific conditions of solar thermal power plants. Turbine manufacturers have pointed out that the use of steam turbomachinery specifically designed taking into consideration the technical and operational constraints of solar thermal power plants could increase the overall plant efficiency, which in turn would increase the competitiveness of CSP plants.

Priority ST.5: Medium-and high temperature systems for industrial solar heat applications

About 40% of the thermal energy consumption in the industrial sector is within the range of 60–300°C. These systems are often relatively small, which results in the demand for a robust and highly automated system to reduce operation and maintenance costs and increase the efficiency of industrial solar heat. The sector still needs the development of highly autonomous solar fields to further reduce maintenance requirements and increase the amount of thermal energy delivered to the industrial process.

Priority ST.6: Thermochemical production of solar fuels

Concentrated solar energy systems can be employed in the thermochemical production of ‘solar fuels’ (any chemical compound that can react with oxygen releasing energy).

Priority ST.7: Digitalisation of concentrated solar thermal plants

The digitalisation of concentrated solar thermal plants with smart energy meters, artificial intelligence, communication devices, smart control and management tools will need to be strengthened.

Research area: non-concentrated solar thermal technologies

The European solar thermal technology panel (ESTTP) is one of the panels of the renewable heating and cooling European technology and innovation platform (RHC ETIP). In its strategic R&I agenda for solar thermal technologies ([45]), ESTTP defines R&I priorities for non-concentrated solar thermal technologies. The main technological areas are illustrated in the following.

([45]) RHC-ETIP Strategic Research & Innovation Agenda for Solar Thermal Technologies, Final Draft 2022.

Priority ST.8: Development of non-concentrated solar thermal technologies

The focus is on the development of system components for solar district heating and solar heat for industrial processes, as well as on the improvement of collectors and technological solutions for buildings.

Priority ST.9: System integration of non-concentrated solar thermal technologies

The integration of large-scale non-concentrated solar thermal systems and storage is a key aspect. Moreover, there is a need for an optimised design and operation of systems based on solar industrial heat.

Priority ST.10: Digitalisation of non-concentrated solar thermal technologies

Digitalisation impacts non-concentrated solar thermal technologies along the entire value chain. As a result of digitalisation, real-time energy data management will be achieved through cost-efficient, robust, and scalable data collection and communication systems.

Table 2. Solar thermal research areas, priorities, and activities

	Concentrated solar thermal technologies
Priorities	**Activities**
ST.1: Line-focus solar power plant technologies	**ST.1.1 | Component development, process innovation and cost optimization for molten salts systems** The objective is to achieve cost reduction by improved components and operation procedures. Furthermore, the development of a new generation of CSP technology should be fostered. **ST.1.2 | Solar collector fields with silicone oil as heat transfer fluid** The objective is achieving higher operating temperatures and increased plant reliability. The new solutions could also be applied in existing plants.
ST.2: Central receiver power plant technologies	**ST.2.1 | Improvement and optimization of current central receiver molten-salt technology** With this activity, solar thermal electricity cost reduction is generated through lower installation and operation costs. **ST.2.2 | Innovative concepts, materials and components for central receiver molten salt technology** The objectives are to achieve solar thermal electricity cost reduction and to foster flexible electricity generation and storage. Moreover, the development of a new generation of CSP technology is accelerated. **ST.2.3 | Solar tower with particle receiver technology** This activity focuses on innovative heat storage solutions and high efficiency cycle integration. High flexibility can be achieved with temperatures up to 1000 °C.

ST.3: Medium and high-temperature thermal energy storage	**ST.3.1 | Single molten salt thermocline** This activity aims to reduce the costs of dispatchable power and extend the storage duration to achieve baseload generation. **ST.3.2 | Next generation of thermal energy storage technologies** In this activity, costs are reduced and the development of pioneering thermal energy storage technologies is driven forward. The aim is to demonstrate key aspects for integration into CSP plants.
ST.4: Turbomachinery	**ST.4.1 | Development of expansion turbine technologies for advanced CSP power blocks** This activity will focus on the expansion of turbines and technologies specifically designed for CSP plants with improved efficiency, operation, and flexibility. **ST.4.2 | Development of turbomachinery for supercritical CO_2 cycles** This activity aims to develop advanced CSP cycles and power blocks using supercritical CO_2 as working fluid.
ST.5: Medium-and high temperature systems for industrial solar heat applications	**ST.5.1 | Medium temperature systems for industrial solar heat applications** The activity aims to achieve thermal energy costs below 0.04 EUR/kWh in Southern Europe and 0.07 EUR/kWh in Northern Europe for temperatures < 400°C. **ST.5.2 | High temperature solar treatment of minerals and metals** Both process and reactor requirements are defined as part of this activity. The aim is to achieve pilot-scale demonstration with long-term continuous operation and temperatures up to 1000 °C.
ST.6: Thermochemical production of solar fuels	**ST.6.1| Liquid synthetic fuels from solar redox cycles** The objective is to improve the solar-to-fuel efficiency and to realise continuous fuel production. **ST.6.2 | Solar fuels from carbon neutral feedstock** This activity focuses on solar-driven integration and utilization of carbon dioxide from flue gas, biogas or waste gas, combined with carbon looping schemes. **ST.6.3 | Solar particle receivers/reactors and other technologies for solar fuels production** The objective is to investigate the use of solid particles that can work as heat transfer fluid, storage medium, and reactant in many thermochemical processes for solar fuel production. Other technologies based on air, liquid sodium, or supercritical CO_2 could be considered.
ST.7: Digitalisation of concentrated solar thermal plants	**ST.7.1 | Digitalisation of concentrated solar thermal plants** Development of the new generation of characterization, monitoring, inspection, maintenance and control systems easy to integrate in existing and new plants.
	Non-concentrated solar thermal technologies

ST.8: Development of non-concentrated solar thermal technologies	**ST.8.1 | Development of system components for large solar thermal heating systems** This activity focuses on components such as solar collectors, heat transfer fluids, heat exchangers, pumps and controls, distribution systems and thermal energy storage. **ST.8.2 | Improved manufacturing processes for solar thermal panels** Aspects of relevance include the development of more efficient and cost-effective manufacturing processes, crucial for the scalability and affordability of solar thermal collectors. **ST.8.3 | Multifunctional solar heat systems for building integration** Key areas of research include technological solutions, prefabrication, packages of technologies, harmonization of standards and norms, and construction processes. **ST.8.4 | Improved PVT collectors** PV/Thermal (PVT) collectors are a promising hybrid technology, and it is necessary to optimize their performance and reduce their costs. **ST.8.5 | Solar-based zero-emission buildings** The aim is to take further the notion of solar active house and to develop solutions for buildings with a solar thermal fraction higher than 50%.
ST.9: System integration of non-concentrated solar thermal technologies	**ST.9.1 | Integration of large solar thermal systems and storages** This activity focuses on the demonstration of large solar thermal systems coupled to large thermal energy storage systems. Solutions for seasonal storage should also be investigated. **ST.9.2 | Integrated solutions for industrial solar heat < 400°C** The objective is the integration of industrial solar heat with existing processes and the development of innovative processes and supply technologies.
ST.10: Digitalisation of non-concentrated solar thermal technologies	**ST.10.1 | Digitalisation of non-concentrated solar thermal technologies** Development of digital tools and solutions for optimized operation, automated monitoring, and fault detection. Standard specifications for monitoring equipment and digital twins can support quality assurance.

6. SOLAR ENERGY R&I CROSSCUTTING THEMES

The SET Plan is now accompanied by new priorities on crosscutting issues for all renewable energy technologies, in a task force approach. The task forces will focus on **sustainability by design**, **skills development**, **R&I tailored to societal needs**, **digitalisation**, and **market accessibility**. With the work of the task forces, the SET Plan will foster a comprehensive approach to the development and deployment of clean and efficient energy technologies.

Beside the crosscutting issues for which SET Plan task forces are established, there are areas that can be considered as crosscutting and for which common R&I work may bring benefit specifically to the three solar energy sectors examined in this agenda (solar PV, concentrated solar thermal, non-concentrated solar thermal).

Common R&I work can be considered therefore for crosscutting themes such as:

Priority CC1: Environmental impact and sustainability

Ensuring the environmental sustainability of solar energy is crucial and thus the investigation of the life cycle impact of solar technologies including manufacturing, installation, operation, and disposal. It is necessary to reduce the environmental footprint of solar technologies by **minimizing land use, use of resources and habitat disruption**.

Priority CC2: Right to light

In urban areas, developing methods to secure **sunlight access,** starting from sunlight analysis to urban regulations. Securing sunlight access, often referred to as the "right to light," is an important consideration in urban planning and property development to ensure a balance between urbanization, optimization of the use of the solar resource and quality of life for residents.

Priority CC3: Solar resource assessment

Solar resource assessment is a critical component of planning and implementing solar energy projects, and it is **closely linked with climate change considerations**. Assessments can be based on historical data and trends, climate models, temperature effects, weather variability.

Priority CC4: Solar energy potential

An integrated approach to the solar energy potential (e.g., taking account of existing land/building use, system interaction with other technologies) is also important.

Priority CC5: Research and technology infrastructures

Such infrastructures are essential for advancing the development, efficiency, and integration of solar energy solutions, as well as offering **'test beds'** for novel/complex system configurations.

Priority CC6: New business models and social solutions

New business models are needed to push new technical solutions, or even allow their sustainable implementation and use. This aspect can have interactions with almost all solution areas. At the same time, understanding the behaviour of consumers is essential to enable positive effects and to anticipate possible negative effects (e.g., lack of acceptance for individual solutions, or unexpected effects on energy demand or grid stability).

7. CONCLUSIONS

The Commission recognises the importance of solar energy technologies to achieve the EU climate and energy goals, as well as their potential to contribute to stronger industrial competitiveness and to more resilient European supply chains, by enhancing collaboration between the involved countries, industry, higher education institutions and research organizations.

To this end, the Commission calls on ERA and SET Plan countries, the SET Plan Steering Group and all relevant stakeholders (including new actors and task forces as necessary) to: 1) strengthen their collaboration; 2) increase and align their efforts in supporting solar energy R&I, development and deployment; and 3) further contribute to the financing and implementation of this solar energy joint research and innovation agenda, as far as possible through a joint programming approach (for example, the Clean Energy Transition Partnership).

Based on the periodical reports of the two SET Plan implementation working groups on solar PV and on solar thermal and the R&I activities of the EU framework programme, the Commission and the Member States will assess the progress in the implementation of this solar energy joint research and innovation agenda, as well as the state of the art of solar energy technologies. On this basis and at the latest within three years, a possible update of the solar energy joint research and innovation agenda will be considered.