EC Grant Agreement n°609788

CHEETAH

Cost-reduction through material optimisation and Higher EnErgy outpuT of solAr pHotovoltaic modules - joining Europe's Research and Development efforts in support of its PV industry

Deliverable

D2.3 - CHEETAH European strategic research agenda on research infrastructures: to support future needs and disseminated to external stakeholders (policymakers)

WP2 – Fostering the use of existing facilities and expertise

Section 1 – Document Status

Document information

Deliverable name	D2.3 - CHEETAH European strategic research agenda on research infrastructures: to support future needs and disseminated to external stakeholders (policymakers)
Lead beneficiary	1
Due delivery date from Annex I	M48
Actual / forecast delivery date	M48
Dissemination level	Public

Document validation

Name	Organisation	Date	Visa
Franco Roca – WP2 leader	Enea	15.01.2018	OK
Jan Kroon - Coordinator	ECN	16.01.2018	OK

Document history

Version	Date	Modifications	Name
1	12.12.2017	First draft	Jan Kroon
2	21.12.2017	Further elaboration on 1st draft	Nigel Taylor, Ivan Gordon, Franco Roca
3	08.01.2018	Second draft	Jan Kroon
4	15.01.2018	Further elaboration on second draft	WP2 members
VF	16.01.2018	Report finalized and validated	Jan Kroon

Section 2 – Table of content

Section 3 – Publishable summary

PV has emerged as one of the key sources of clean energy at global scale. It stands out from other renewable technologies in terms both of the broad range of technology options and of the scope to significantly improve energy conversion efficiency in the coming years. European R&D now more than ever needs to coordinate its efforts to maintain its leading position at global level and to continue to provide the basis for a strong European PV industry and commercial sector.

Taking advantage of the broad experience of the 35 R&D organisation taking part in the Cheetah project, this report describes four main categories of research infrastructures related to the development of the full value chain of photovoltaics. Within these categories a number of subtopics are listed, with a description of background and current trends, an overview of existing RI within the Cheetah/EERA PV consortium and reommendations for the future per subtopic. It also address the role of Quality Infrastructure as an essential component in the continued development of PV.

For an efficient use of all the individual research infrastructure listed in this report, there might be oppportunities to create virtual research infrastructure networks in Europe where several research organizations can join forces to work on common topics in e.g. indoor/outdoor device characterization, reliability testing by sharing equipment and available skills and expertises. This type of networking will be very beneficial for a common and effective definition of the future European strategy on PV Research Infrastructures.

This report complements the recently published SET-Plan implementation plan for PV, produced by the Temporary Working Group comprising representatives of the EU Member States, industry, the research sector and academia. This implementation plan describes in general terms the (non-) technological R&D activities needed to achieve the overall strategic targets as defined in the SET plan Declaration of Intent.

This report is targeted at public and private funding agencies who make decisions on the allocation of research budgets. Where appropriate the Research infrastructure agenda should be taken up by ESFRI (European Strategy Forum on Research Infrastructure) in next updates of its roadmap), with a view to set up a whole range of multi-purpose RI, addressing the whole PV value chain form the lab to the fab all along the TRL scale. It should further enable flexible cooperation and optimal use by European user communities.

Section 4 – Executive summary

Description of the deliverable content and purpose

See public summary in section 3.

Brief description of the state of the art and the innovation brought

The European Commission is setting up relevant efforts to sustain specific platforms where the European scientific community and European industry can work and innovate together in each branch constituting pillars for the growth and job highlight in Europe. For this reason the definition of the technical-scientific necessities of equipment and research infrastructures has been a key point of the Coordinatian activities in CHEETAH project to provide a joint program aiming at enhancing the strategic use of PV resources and reinforcing cooperation and synergies.

The starting point has been the complete and comprehensive assessment of user needs and demands by the evaluation of available infrastructures and protocols (D2.5) and execution of actions plan to stimulate expertise and infrastuctures exchange (D2.6).

The valuable experience gathered in the European project on Research Infrastructure SOPHIA has been further elaborated within CHEETAH by launching surveys to inventorize Infrastucture needs (D2.7, D5.8) and using the guidelines set by EERA PV and the SET-Plan Temporary Working group PV Implementation Plan. This has all been incorporated in the vision proposed by this report that supports all the present and future needs of research Infrastuctures for PV in the industrial sector and scientific community.

Section 5 – Deliverable report

1 Introduction

This CHEETAH task on the development of a European strategic research agenda on research infrastructures for photovoltaics is aimed at checking if the existing facilities fulfil all the present and future needs of the industrial sector and scientific communities. It starts from the document « Strategic vision on photovoltaic research infrastructure » that was published in 2014 in the frame of the SOPHIA project, and can be considered an update of this original document. Such an update was needed since in the last 3-4 years, many things have changed both in the PV industry as well as in the PV R&D field.

This document addresses four main categories of research infrastructures related to the development of photovoltaics:

1. Specific laboratory equipment for new processes for PV technologies: silicon wafer, thin film (including organic and hybrid organic), multi-layer concepts.

2. Major and outstanding tools such as supercomputers, simulation software or advanced characterisation equipment (e.g. high performance computation, synchrotrons).

3. Demonstration equipment or pilot lines for larger-scale processing.

4. Test facilities for PV modules and systems performance and lifetime characterisation (also addressing the growing class of integrated PV applications: building integrated PV, PV in electric vehicles, PV in autonomous devices, infrastructure integrated PV).

The report also considers the role of "quality infrastructure", which includes European and international standards, testing methods and metrology, all areas in which research has an important role in ensuring continuous improvement.

The list of infrastructures presented in this document is based on the input from the partners of the Cheetah project and the partners of the joint program on photovoltaics from EERA (European Energy research Alliance, www.eera-set.eu). Therefore, this list does not contain the PV infrastructure of companies based in Europe, and it does not contain all research infrastructure of all R&D research centers or universities. Nevertheless, our list does cover a very substantial and relevant part of the European PV infrastructure and is extracted from the dynamic database to be found in the CHEETAH knowledge exchange portal that was created in the frame of the Cheetah project (https://www.cheetah-exchange.eu/).

When it comes to identifying the current and future needs of the European PV industry in terms of research, we have based ourselves on the SET-Plan TWP PV Implementation Plan, published at the end of 2017. This Implementation Plan describes the technological and non-technological R&I activities that need to be implemented in order to achieve the strategic targets adopted in the SET-Plan Declaration of Intent (DoI) on PV[i], as agreed in December 2015 by the SET-Plan Steering Group and representatives of the SET-Plan stakeholders most directly involved in the PV sector. As such, this Implementation Plan can be considered as the roadmap for future European PV R&I, drafted by the European PV industry, research and public authorities.

2 Laboratory equipment for new processes for PV technologies

2.1 Silicon PV Technology

This part deals with wafer-based crystalline silicon PV technology and comprises the silicon material and wafer fabrication, the cell processing, and the interconnection and encapsulation of cells into modules. As such, this part is in line with R&I activities No. 2 (Technologies for silicon solar cells and modules with higher quality), No.3 (New multi-junction PV technologies for highest efficiencies at reasonable costs) and No 5 (Manufacturing technologies) of the SET-Plan TWP PV Implementation Plan.

2.1.1 Background[ii]

Wafer-based silicon (cSi) technologies have the largest market share (>90%) in the worldwide PV sector. Since this very large market share will remain in the coming decade, this is a very important technology for further research and innovation. The main objective of further research in the field of cSi PV technology is to develop and implement advanced cSi PV processes for high-performance and high-quality cells and modules in high-throughput industrial manufacturing processes, including (for the sector) new materials and production equipment. These high-quality modules will serve as differentiator for the European PV industry by means of significant efficiency benefits and better performance related to sustainability aspects and recyclability of modules (PV Ecolabel, Ecodesign and Energy labels).

Silicon feedstock and silicon wafers

Concerning silicon feedstock technology, the Siemens process is still dominating the market, but the market share of the fluidized bed reactor (FBR) is expected to continuously increase. However, the latter technology still needs a lot of further development. The Upgraded MetallurGical Silicon (UMG Si) will also increase it market share, as long as it demonstrates its benefits in terms of cost and energy-consumption.

The throughput of the crystallization process can be further increased by increasing the common size of the ingots. A transition from Gen6 to Gen7 (with mass of ingot of up to 1000 kg) for mono-Si is expected in mass production in the coming years, and for multi-Si a transition to Gen 8 (1200 kg) is expected by 2020.

Concerning wire sawing, slurry-based wire sawing is still the dominating technology in the market. However, diamond wire sawing is already the mainstream technology for mono-silicon wafering and is expected to completely replace slurry-based wafering from 2019 onwards. Diamond wire sawing of multicrystalline silicon is expected to steadily gain market share over slurry-based wire sawing over the next 10 years but here challenges in wet chemical texturing need to be overcome first by targeted R&D.

Si wafers account for about 40% of the current total module cost. Therefore reducing the wafer thickness and reducing the kerf losses can lead to substantial cost reduction. This requires substantial further technology developments. Ultimately, kerfless wafering techniques like epitaxial lift-off will enable ultra-thin high-quality wafers to be made, shortcutting a large part of the silicon wafer value chain.

Silicon solar cells

More and more advanced technologies and cell designs are under development, including PERC, PERT, PERL, HJT, IBC and HJT-IBC processes. These technologies are characterized by increasing complexity but also by increasing maximum efficiency potential. A key to commercial success for all these technologies is to reduce the production costs linked to the increased process complexity. A move towards bifacial cells and modules with increased energy yield could further help in this. Innovation is required to simplify and further develop the necessary high-throughput processes.

In addition to the need for new production processes, there is an increasing need for more and more detailed characterization methods. This includes determination of performance over meaningful volumes (average, max, distribution), manufacturing yield, etc.

Since the above-mentioned technologies will push the efficiencies of silicon solar cells close to the practical efficiency limit, there is an increasing effort to develop breakthrough technologies which will allow silicon solar cells to surpass these practical limit. In particular, the silicon-based multijunction approach in which a high-bandgap III-V or thin-film (e.g. perovskite) solar cell is placed on top of a silicon solar cell is being researched more and more, since this approach will allow on the long term to make silicon-based solar cell devices with efficiencies well above 30.

Silicon modules

The costs of silicon module production are dominated currently by material costs. Both improvements in module performance and reductions in material costs are therefore required. Research to increase module performance should focus on the reduction of optical losses (e.g. improved AR-coated glass) and the reduction of interconnection losses. Since a wide variety of cell architectures are currently being developed (see above), optimized and in some cases novel interconnection schemes are needed for each of these cell types. These interconnection schemes also need to be compatible with the thinner and thinner wafers that are expected to be used in future. Approaches for reducing material costs include reducing the amount of material used, engineering of new low-cost materials, and material waste reduction. In particular, the cost of the encapsulation and backsheet materials used should be lowered, without deteriorating the reliability and lifetime of the ensuing module. The cell to module power ratio is expected to exceed 100% in the future due to further improvements in light management within the module and improved encapsulant and interconnection technologies. Finally, the ease of recycling end-of-life PV modules should be taken into account as a design parameter during the development of novel PV module technology.

2.1.2 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
3	CEA	CEA-INES SUSI platform	• Crystallisation and wafering processes • Silicon ingot and wafer characterisation	Le Bourget du Lac Cedex | France
46	iCUBE	iCUBE-MAPECV Research Infrastructures	• Synthesis of material • Realization of solar cells	Strasbourg | France
55	IFE	IFE-IFE Solar Cell Laboratory	Laboratory for the processing and characterization of solar cells and solar cell materials.	Kjeller | Norway
-*	FZJ	FZJ- Silicon heterojunction baseline	Covering the whole chain of the SHJ solar cell fabrication from the wet-chemical preconditioning of crystalline silicon wafers to the growth of functional thin-films and the final post-deposition thermal treatment	Jülich | Germany
-*	FZJ	FZJ - PECVD+HWCVD systems for SHJ	• 6-Chamber system • Cluster deposition tool (CT1) • Electron Spin Resonance • p-HW Chamber	Jülich | Germany
29	METU	METU-Center for Solar Energy research and Applications	Fabrication of: • Very high efficiency c-Si solar cells besed on PERC ann IBC concept • a-Si , CIGS based solar cell.	Ankara | Turkey
18	SINTEF	SINTEF-Heliosi Characterization	Silicon characterization, including raw material, ingot and wafer characterization	Trondheim | Norway
5	SINTEF	SINTEF-Heliosi Crystallisation	Silicon crystallization, including multicrystalline and monocrystalline silicon	Trondheim | Norway
54	TUBITAK	TUBITAK - Marmara Research Center, Fotonic Technologies Laboratory	deposition systems and equipments for the fabrication, development and characterization of photovoltaic cell and modules.	Gebze, Kocaeli | Turkey

28	UNIMIB	UNIMIB-Milano-Bicocca Solar Energy Research Center	• Realization and characterization of Materials and devices related to solar energy in its various forms	Milan | Italy
50	UPM	UPM-Cell manufacturing and characterization	Solar cell manufacturing and characterization facilities	Madrid | Spain
27	UPM	UPM-Silicon production	Semi-industrial plant for silicon purification, synthesis, crystal growth by the Czochralski method and characterization	Madrid | Spain

*These infrastructures are not already included in CHEETAH KEAP catalogue

2.1.3 Recommendations

Concerning silicon feedstock and wafers, more European infrastructure is needed for the following topics:

- A facility for novel silane-based and trichlorosilane-based production technologies would enable further developments within emerging silicon production technologies.
- A facility for umg-material development at the research scale is needed to ensure the availability of material developed at the forefront of research on umg-silicon.
- Updated high-performance crystallization facility, and in particular furnaces constructed for maximum control over the crystallisation process, both for Cz and high-perfromance multi technologies. Tiny variations in temperature can cause changes in crystal structure and therefore material performance.

Concerning silicon solar cell technology, there are many different complete processing lines spread accross Europe that cover the various high-efficiency silicon cell concepts such as PERC/PERT, IBC, heterojunction. There is no real need here for new infrastructures but rather a need for alignment of these different infrastructures to streamline high-efficiency cell development within Europe. Moreover, in view of reaching the long-term goal of highly efficient tandem devices consisting of high-bandgap thin-film cells on top of silicon bottom cells, these silicon cell infrastructures should strongly start interacting with thin-film infrastructures to allow for specific development needs to establish these tandem devices.

Concerning silicon module technology, it is becoming more and more important to be able to guarantee 30 to 40 years lifetime guarantees for modules and to be able to predict the energy yield throughout operation. This part will be addressed in section 5.3.

2.2 Thin film PV

This part deals with thin film PV technology and comprises all the activities related to thin film PV cell and module processing for thin film Silicon, CIGGS, CdTe and CZTS Kesterites. As such, this part is in line with R&I activities No 3 and No 5 of the SET-Plan TWP PV Implementation Plan.

2.2.1 Background

Most thin PV modules consist of monolithically series connected thin film solar cells, which can be deposited directly on large area substrates, such as glass panels, ceramics or foils. The main technologies of interest are:

- *CIGS*-Copper indium gallium diselenide: a highly promising alternative to silicon in terms of efficiency record (currently at 22,6%), low temperature coefficient and excellent performance also under low light conditions.
- *CdTe*-Cadmium telluride: polycrystalline thin film solar cells have shown an immense potential in scalability by reaching its maturity for industrial production. Modules have demonstrated long-term stable performance and high efficiency up to 22%.
- *CZTS*-Kesterite: kesterites are tetrahedrally coordinated quaternary semiconductors very similar to $Cu(In,Ga)Se_2$ (CIGS) but indium is substituted by the zinc-tin pair. So far they show limited efficiency.
- *TFSi*-Thin Film Silicon technology is based on a versatile set of materials and alloys, in both amorphous and microcrystalline form, grown from precursor gases by means of a capacitively coupled plasma.

Current and future R&D issues facing thin-film photovoltaics are to be found in the areas of material and device performance, equipment and manufacturing issues as well as sustainability and device characterization. The research ranges from fundamental science at the lab scale to the development of industrial processes and equipment. While all thin film technologies have some common features like large area substrates, TCOs and the monolithic series connection, they differ considerably in the processing methods. Therefore it is difficult to define generic research infrastructure for materials development and manufacturing.

Nevertheless two topics of common interest are the field of TCO and light management. TCOs are applied in all thin film devices and multijunction devices (see also section 2.4) and they are crucial for efficiency because they need to offer high optical transmission and high conductivity, which are contradicting demands.

When thin film devices are further reduced in thickness to save material, back reflectors become necessary to maintain a high short circuit current. In addition, the light management is governed by textured interfaces, which are sometimes introduced by the TCOs. However, textured glass, textured silicon wafers or nanotechnology are also applied to induce light scattering.

For characterisation of electrical performance most thin film modules must be pre-conditioned as they may be in a metastable state. Test procedures and measurement protocols have to fulfil the aims of different worlds: the manufacturing, the qualification and the application in the field.

2.2.2 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
58	CIEMAT	CIEMAT- Chalcogenide Lab	Preparation and characterization of thin-film TCOs (ITO, ZnO:Al, SnO2:Sb) and chalcogenides (CIGS, ZnS, SnSx).	Madrid | Spain
56	CIEMAT	CIEMAT-TFSi Lab	Preparation and characterization of thin-film Si (a-Si, µ-Si) , TCOs, metallizations and interconnections	Madrid | Spain
-*	EMPA	EMPA-Laboratory for Thin Films & Photovoltaics	• CuIn1-xGaxSe2 – Flexible and Lightwe /Switzerlandgh Solar cells • CdTe Solar Cells • Solar cells made from Cu2ZnSn(Se,S)4 a • Functional Inorganic Materials	Dübendorf | Switzerland
23	ENEA	ENEA-Facilities for depostion of TCO by sputtering and MOCVD	Development and realization of TCO by Sputtering, MOCVD and by spin coating for rigid and flexible substrates	Portici(NA) | Italy

22	HZB	HZB-TCO sputter deposition 30 x 30cm2	Deposition of ZnO and ZnO:Al for small area cells and module test structures	Berlin | Germany
-*	HZB	HZB-HySPRINT	• Hybrid Silicon Perovskite Research, Integration & Novel. Technologies. • Liquid Phase Crystallized Silicon on Foreigh Substrate (LPC)	Berlin | Germany
-*	HZB	PVcomB	• Competence Centre Thin-Film- and Nanotechnology for Photovoltaics • 30 x 30 cm² solar modules based on thin-film silicon and CIGS as well as 5- and 6-inch silicon heterojunction cells	Berlin | Germany
46	iCUBE	iCUBE-MAPECV Research Infrastructures	• Synthesis of material • Realization of devices (diodes, transistors, memories, solar cells) • Characterization and modeling	Strasbourg | France
26	IKZ	IKZ-FVB Infrastucture for the preparation of Silicon and CIGS precursors	• Growth of crystalline silicon on amorphous substrates • Preparation of precursors for CIGS microconcentrator solar cells	Berlin | Germany
9	LNEG	LNEG-PV technologies lab	• Equipment for PV Cells development and material characterization.	Lisboa | Portugal
29	METU	METU-Center for Solar Energy research and Applications	Fabrication of: • a-Si , CIGS based solar cell.	Ankara | Turkey
54	TUBITAK	TUBITAK - Marmara Research Center, Fotonic Technologies Laboratory	deposition systems and equipments for the fabrication, development and characterization of Thin film solar cells.	Gebze, Kocaeli | Turkey
31	TUT	TUT- Electrical, structural and optical characterization of PV materials	• Lab for extensive electrical, structural and optical characterization of PV materials and devices • Electrical, structural and optical characterization of materials and devices based on kesterite (CZTS), chalcopyrite (CIGS) and cadmium-telluride (CdT)	Tallinn | Estonia

28	UNIMIB	UNIMIB-Milano-Bicocca Solar Energy Research Center	• Realization and characterization of Materials and devices related to solar energy in its various forms • Sputtering, Joule and hybdrid co-evaporation techniques to deposit CIGS thin film on several substrates(Flexible , PI , Glass) • Solution deposition system (via Sol- gel and drop) of Kesterite (CZTS and CFTS)	Milan | Italy

*This infrastructure is not included yet in CHEETAH KEAP catalogue

2.2.3 Recommendations

TCO and light management

- Research Infrastructure is needed in Europe to coordinate research and improve understanding of materials and limits to obtain improved or sustainable materials and concepts that fit the needs of various technologies (including the multijunction approach)
- Characterisation: Define common standards for the characterization of TCOs (absorption, sheet resistance)
- Light management requires specific characterization methods.
- Methods for light trapping
- TCO network: Improved TCO composed of abundant materials requires detailed understanding of transport limitation, degradation mechanisms and preparation processes. Therefore a network of TCO experts must be established in order to use existing infrastructure more effectively and merge insights from different viewpoints of applications.

2.3 Organic and hybrid organic

This part deals with organic and hybrid PV technology and comprises all the activities related to Organic and hybrid (Perovskite, DSSC) PV cell and module processing As such, this part is in line with R&I activities No 3 and 5 of the SET-Plan TWP PV Implementation Plan.

2.3.1 Background

The technologies covered here are:

Organic solar cells (OPV) use carbon based materials, typically in forms of small molecules, dendrimers and polymers, to convert solar into electric energy. This enables the low cost production and energy processing. Additional advantages of OPVs are the light weight and flexibility. Efficiencies up to 13% have already been achieved for OPV devices. The lifetime remains among the main bottlenecks with respect to inorganic approach, but it will be significantly improved before the commercialization.

- DSSC-Dye Sensitized Solar Cells: Dye-sensitized solar cells (DSCs) are photovoltaic cells consisting of a dye that absorbs sunlight and a mesoporous TiO2 layer and a liquid/solid electrolyte that transport carriers to opposite electrodes. DSCs are especially suited for building and automobile integrated PV as they can be made into semi-transparent coloured glass facades and portable or indoor light harvesting applications since they possess remarkable efficiencies under these conditions.

- CH3NH3PbX3–Perovskite: Hybrid perovskites are an upcoming class of organic/inorganic materials which shows a strong absorption in a broad region of the visible spectrum, a good electron and hole conductivity, and delivering also high open circuit voltages in photovoltaic devices. Providing those characteristics, a plethora of solar cell layouts have been explored and outstanding power conversion efficiency of 22.7 % has been recently certified.

Today, cell efficiencies at the lab scale are at an exceptional pace, but on module level the performance is still lagging behind. Directing the effort towards the module-scale can significantly decrease the gap between the cell and module efficiencies. While the field of organic photovoltaics is focusing on upscaling, and the number of sites with installed large-scale printing and coating machinery is rapidly increasing, the field of perovskite technology still needs to define the precise path for upscaling.

OPVs, DDSCs and perovskites have specific needs for testing equipment and the associated "software" for data management, meaning protocols, standards, procedures. Facilitation of installation of small-scale solar parks and field test facilities is important. The conditions should be that the owners of the facilities allow extensive access to research teams to perform tests on the devices *in situ*. Such tests are vital to demonstrate the potential and applicability of the technologies in real life applications. Strong support by e-infrastructure, such as simulation tools, databases, data analyses tools etc. is necessary as well.

2.3.2 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
2	CEA	CEA-INES OPV Infrastructure	• fully inkjet manufactured flexible organic PV modules • Ageing behaviour of organic PV cells in accelerated conditions • Barrier and ultra-barriers measurements with high sensitivity	Le Bourget du Lac Cedex | France
14	DTU	DTU-Characterisation Laboratory for Organic Photovoltaics (CLOP	• Full set of testing equipment for the performance and lifetime characterization according to ISOS protocols • Device lifetime and energy output from ageing curves	Roskilde | Denmark
13	DTU	DTU-Processing and Characterization laboratories for organic PV	• Processing organic PV in polymer solar cells; Roll-to-Roll printing and coating • Characterisation; advanced studied on structure, optical properties and chemical composition • Software for calculating device lifetime and energy output from ageing curves	Roskilde | Denmark
34	ECN	ECN-Solliance OPV Infrastructure	• OPV process lines: Characterization lab, including controlled aging of devices	Petten | the Netherlands
7	ENEA	ENEA-Portici Infrastructure for Organic PV	• • Processing and characterization of organic photovoltaics (OPV) in various configurations • Testing of Organic and hybrid Electronic devices	Portici(NA) | Italy
39	FhG	FhG-ISE Production Technology for Organic Solar Cells Infrastructure	• Development of device stacks and module structures for low cost, stable and highly efficient OPV	Freiburg | Germany

25	IMEC	IMEC-Organic-Line Infrastucture	• OPV material and architecture evaluation • Upscaling towards inline processing of OPV modules	Genk | Belgium
9	LNEG	LNEG-PV technologies lab	• Equipment for OPV Cells development and material characterization.	Lisboa | Portugal
29	METU	METU-Center for Solar Energy research and Applications	• Fabrication of: • Organic PV and, DSSC	Ankara | Turkey
33	NPL	NPL-Photovoltaics and Organic Electronics Infrastructure	• Handling, realization and characterization of Organic Devices in controlled environmentally.	Teddington | United Kingdom
8	TECNALIA	TECNALIA- OPV solar cell processing and characterization facility	• OPV Cell/module encapsulation, characterization and aging	Donostia | Spain
28	UNIMIB	UNIMIB-Milano-Bicocca Solar Energy Research Center	• Realization and characterization of Materials and devices related to solar energy in its various organic and hybrid forms. • DSSC Solar cells	Milan | Italy
36	UTV	UTV-Centre for Hybrid and Organic Solar Energyâ€ (CHOSE)	• Research and development for the industrialization of organic and hybrid organic-inorganic technologies • Batch Pilot Line production of Perovskite and DSSC modules	Rome | Italy
24	VTT	VTT-Polymer solar cell processing facility	• • R2R processing for OPV cells/modules • Material performance testing and up-scaling into pilot scale	Oulu | Finland

2.3.3 Recommendations

Stability and upscaling are considered as the main challenges for Organic and Perovskite based PV to become a commercial viable option with widespread use. Especially Perovskites have the potential to form an efficient tandem configuarion when combined with more established technologies like wafer based x-Si. In order to accelerate the progess for these emerging technologies, the research towards lifetime improvement and upscaling should be intensified using dedicated research Infrastrure for upscaling and lifetime improvement:

Upscaling: Scalable processing equipment, pilot lines, scalable lamination, scalable testing equipment

Stability: Testing setup (ageing chambers, outdoor platforms, advanced solar simulators, IV tracers, etc., simulation analyses, databases), build up of databases of materials for barriers and adhesives, device lifetimes, simulation tools (e-infrastructure)

2.4 Multi-layer multi-technology concepts

This part deals with the development of novel multi-layer multi-technoogy concepts (tandems). As such, this part is in line with R&I activities No. 3 and 5 of the SET-Plan TWP PV Implementation Plan.

2.4.1 Background

III-V Multijunction solar cells are, and have been over the past two decades, the most efficient photovoltaic devices manufactured to date. In multijunction solar cells materials with different bandgaps, namely subcells, are stacked to absorb and convert different fractions of the solar spectrum with maximum efficiency. Today's industry standard is a triple-junction solar cell and four-junction devices appearing in the horizon. A well-established research infrastructure exists for the study and characterisation of these devices in concentrator systems.

The short term interest is currently however more focussed on tandem concepts capable of reaching efficiencies above 30% that are capable of being scaled to large areas. This includes silicon wafer tandems with III-V materials or organics or perovskites, or thin film CIGS or CdTe with perovskites.

In multi-junction devices, partially selective reflectors are applied. Light trapping is relevant to wafer based and thin film silicon technology and is becoming increasingly important for other absorber materials in thin film technology as well. The infrastructure and available methods and standards of nano-optical characterization of rough interfaces, plasmonics and optical modelling must be expanded to approach all thin film technologies including OPV.

Mulitlayer or multijunction thin film devices present a further range of challenge for reliable performance characterisation, but an area that is destined to be increasingly important as we push to higher efficiencies. Such devices require flexible spectral response measurement systems and for the power measurement itself, spectrally tunable simulators are desirable, together with appropriately matched reference cells for device devices being tested. Appropriate measurement routines for new equipment or new device classes have to be defined.

2.4.2 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
49	UPM	UPM-Epitaxial growth	• Epitaxial growth of PV materials and cells • Metal Organic Vapour Phase Epitaxy (MOVPE) and Molecular Beam Epitaxy (MBE).	Madrid | Spain
38	UPM	UPM-IB Solar Cell lab	• Advanced characterisation of photovoltaic materials and solar cell devices • Intermediate Band Materials and Solar Cells Characterisation Laboratory • Device processing.	Madrid |Spain
28	UNIMIB	UNIMIB-Milano-Bicocca Solar Energy Research Center	• EQE for measurements on multijunction solar cells (expertize in performing EQE in 3-4J based on III-V material for space application	Milan | Italy
44	ENEA	ENEA-Indoor/outdoor characterization facilities for CPV solar cells. modules and optical elements	• Characterization facility for electrical and optical performance analysis of solar cells, CPV modules and optical concentrators components • EQE for measurements on multijunction solar cells	Portici(NA) | Italy
36	UTV	UTV-Centre for Hybrid and Organic Solar Energy (CHOSE)	• Fabrication and characterization of tandem Perovskite/Silicon cells on small and large area.	Rome | Italy
-*	FhG-ISE	FhG-ISE- III-V Epitaxy and Solar Cells	• World record III-V solar cell • Epitaxial growth of III-V semiconductor materials on III-V, Ge and Si substrates. • Solar cells optimized for specific applications – (satellites, PV concentrator systems and laser power beaming)	Freiburg | Germany

-*	FhG-ISE	FhG-ISE- CalLab PV Cells	• Characterization of III-V Solar Cells and Concentrating PV • Spectral response of multi-junction photovoltaic cells • Calibrated I-V curve measurement	Freiburg | Germany
-*	Imperial C	Quantum Photovoltaics Group	• High efficiency concentrator solar cells. • Multi-junction solar cells - novel sub-cell materials & nanophotonic enhancements • Up conversion & intermediate band solar cells • Theory and proof of principle of other high-efficiency solar cell concepts	London |United Kingdom

*These infrastructures are not already included in CHEETAH KEAP catalogue

2.4.3 Recommendations

The multi-junction approach is considered as the way to go significantly beyond the maximum efficiencies of single band gap absorbers and is part of the roadmaps of many research groups and companies. This is an emerging research area and it combines several of the technology advancements already made for the individual PV technologies as mentioned under sections 2.1 until 2.3. For a dedicated development and optimization of the various tandem concepts, all the following research subtopics are important,

- Materials, device and systems simulation
- Preparation of bottom (wafer-based or thin film) and top cell (thin film) materials
- Preparation of tunnel junction and TCO materials
- Analysis of materials, interfaces, characterization of cells and modules
- Lifetime assessment, stability, ecological footprint
- Long-term outdoor performance and yield prediction
- BIPV
- Grid integration

For the optimization of the bottom and top cells and integration into one device, all the tools for materials preparation, surface and interface analysis and simulation, testing and upscaling relevant for the individual technologies listed under section 2.1-2.3 can be used. The characterization part requires dedicated solutions like designing specialized sun simulators for multijunction characterization with the aim to developing/expanding pre-normative stability testing standards.

3 Major analytical tools

3.1 Computational Materials Science

Computational materials science, typically coupled with high performance computing, has an important role to play in developing innovative PV devices and products. In this context a virtual materials lab can design new materials and provide recipes for improved materials based on predictive modelling. For instance, there is a need to explore new materials and processes for economic and sustainable TCO materials or for improving stability and sustainability of organic and hybrid organic PV systems.

Many of Europe's leading institutes working on PV use in-house computational tools as an integrated part of their research efforts, supported often also by dedicated experimental facilities. The SET-Plan PV Implementation Plan (2017) foresees the possibility to initiate a (virtual) high performance computer centre for PV R&I.

The European Technology Platform for High Performance Computing (ETP4HPC), and the ESFRI Landmark PRACE (e-RI) facilitate high-impact scientific discovery and engineering research and development across all disciplines.

3.1.1 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
19	ECN	• ECN-Cell en Module modelling infrastructure	• Numerical device simulations of cSi silicon solar cells • Yield modeling Bifacial cells and modules	Petten | the Netherlands
15	ENEA	• ENEA-GRID High performance computational infrastructure	• High performance computational for parallel computing and numerical analysis • visualization and data mining	Portici | Italy
20	FZJ	• FZ-Jülich Modelling and Simulation at Supercomputing Centre (JSC)	• Large-scale, computation-intensive material and device simulations for photovoltaic applications	Jülich | Germany
16	IMEC	• IMEC-Cell Modeling infrastructure and software	• Electrical and optical characterization of wafers • FE modeling of thermo-mechanical effects and stresses	Leuven | Belgium
36	UTV	• UTV-Centre for Hybrid and Organic Solar Energy (CHOSE)	• TIBERCAD a Multiscale/Multiphysics Software for Optoelectronic devices including solar cells	Rome | Italy

3.1.2 Recommendations

1) Develop a stategy for a (virtual) high performance computer centre for PV R&I, as proposed in the SET-Plan Implementation Plan 2017.

2) Promote clustered activities between EU centres of excellence for computation materials science for PV, to address for example:

- Catalogue available programs and their development status (complete / under construction etc)

- Commong acces to databases of empirical data for various material systems and PV technologies
- Development of multi-scale modelling tools, in particular for modelling nano-structured solar cells and inclusion of ab-initio material models in device level models.
- Round-Robin test of computational models

3.2 Major Facilities for Advanced Materials Characterisation

The ESFRI 2016 roadmap notes that Europe hosts a range of large-scale analytical research infrastructures relevant to material physics and materials science research. These include:

- Light sources based on electron accelerators and storage rings provide brilliant soft to hard X-ray beams enabling nanoprobes of the structure and chemical composition of materials.
- Neutron and muon sources based on proton accelerators and nuclear reactors to probe the structure and dynamics of materials.
- Broadly distributed laser spectroscopy, high resolution electron microscopy, NMR, ion beam and nanoscience facilities

3.2.1 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
17	HZB	HZB-UHV-end station for preparation and analysis of thin films for PV at BESSY II (CISSY)	• Synchrotron radiation source BESSY II, producing ultrabright photon beams ranging from Terahertz to hard X-rays and x-ray lab sources for the characterizationof materials and interfaces	Berlin |Germany

3.2.2 Recommendations

Major advanced materials research infrastructures relevant for PV should be specifically promoted in the ESFRI (European Strategy Forum on Research Infrastructure) Roadmap.

3.3 Performance Databases

3.3.1 Solar Resource

Large geospatial datasets on solar resource (and associated PV output) are now publicly available, also covering extended time periods. Such information can be used analyse impact of high-penetration deployment. The JRC's PVGIS calculation tool uses CMSAF data to provide hourly data for a representative year at any location in Europe, Africa and most of Asia. The JRC's EMHIRES database provides 30 years of hourly data on PV capacity factors for the whole EU with a spatial resolution on 3 arc-minutes.

Solar resource and solar power forecasting is an area of increasing importance, with active research onNumerical Weather Prediction (NWP), Model Output Statistic (MOS) approaches and satellite-based forecast models. Data (both model input and output) is typically closely controlled by the organisations involved.

3.3.2 Outdoor Performance Assessment Data

Many research organisation collect data from long term outdoor peformance test on individual modules or small demo systems. In the SOPHIA project (2011-2014) a common database on such data was set up, but unfortunately has not been continued.

3.3.3 System Operational Data

Operational PV systems represent a goldmine for data on performance (meaning the module, inverter and other components in the system). This could, for example, help relate the failure modes of modules (or reductions in performance) to the environmental stress at a given location. Furthermore it is in the overall interest of the PV sector and of society that knowledge of the performance of PV technology is improved.

Up to now, operators and component manufacturers have largely kept PV plant performance data confidential, as part of their competitive advantage Putting data in the public domain brings a common benefit in terms of reduced risk and hence investment costs.

Until such a system is realised, the main source of freely available operational data is from publicly supported schemes:

- In France, the operators of PV power plants are obliged to provide performance data in order to get the feed-in tariff. CEA collects data of more than 100 large scale power plants. However, these data are confidential.
- For demonstration projects funded under the NER300 instrument e.g. the 24 MWp CPV plant "Santa Luzia Solar Farm" in Portugal, knowledge sharing is a condition for the award.
- Internationally, IEA PVPS Task 13 has created a database of system performance.

3.3.4 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
13	DTU	DTU-Processing and Characterization laboratories for organic PV	• OPV Performance and Degradation Database	Roskilde | Denmark

30	JRC	JRC-European Solar Test Installation (ESTI)	• PV-GIS on-line tool (geospatial solar and PV resources, typical metrological year data) • EMHIRES dataset (30-year datasets for wind and solar PV in the EU	Ispra | Italy

3.3.5 Recommendations

A concerted effort is needed to convince the PV community that publicising plant operation data brings a common benefit in terms of reduced risk and hence investment costs. A possible starting point could be systems installed on public buildings or other sites, as well as plants operated for research purposes with public funding. Crowd-sourcing could be used to access residential and commercial rooftop systems.

EU research organisations should be encouraged to pool data generated from module testing and from small demonstration plants.

4 Demonstration production equipment or pilot lines for larger-scale processing

This part is in line with the R&I activity N° 5 of the SET-Plan TWP PV Implementation Plan.

4.1 Background

One of the strategic targets of the SET plan is to realize major advances in manufacturing and installation by:

- Making available GW-scale manufacturing technologies that reach productivity and cost targets consistent with the capital cost targets for PV systems;
- Developing PV module and system design concepts that enable fast and highly automated installation, to reduce the installation costs of both ground-mounted arrays and PV building renovation solutions, by 2020.

Based on this strategic target, the Temporary Working defined amongst others a list of R&D activities dedicated to realize manufacturing solutions for x-Si and thin film supporting the prioritized strategic target. Further implementation of high-throughput, high yield industrial manufacturing technology will further reduce the LCOE and include production equipment (Capital Expenditure; CAPEX) and material (Bill of Materials; BOM) costs as well as product quality (efficiency and performance). The introduction of new materials and cell/module designs enforces advances in the field of manufacturing technologies and will also strengthen the European manufacturing equipment industry.

To realize these targets, (pre-)pilot-lines are very interesting everywhere along the whole value chain from materials suppliers to end-users through equipment, device and system integration companies. These lines can be used to test the efficiency and cost of major processing steps and bring the TRL from 6-7 to the required level of industrial production at TRL9. This will include

- Silicon crystal growth techniques
- Cells and modules, for both thin-film and silicon technologies
- Low cost, large-area deposition process equipment
- laser technology and control methods

These pilot lines must be regularly upgraded, expanded or replaced to keep pace with technological progress. In the last years, this has already led to the establishment of a number of (large-scale) pilot production lines in Europe which are crucial for co-developing and to assess the manufacturability of novel manufacturing processes for different PV technologies (x-

Si, CIGS, TF-Si and OPV), cell interconnection concepts (HIT, MWT, IBC, other) and module and product manufacturing (glass or polymer lamination, vacuum-based or resin-based processes, etc.) at representative scales ahead of their transfer to industry. Examples of existing pilot development lines in Europe are the Heterojunction c-Si pilot line for cells and module installed at CEA/INES, the PV-TEK pilot production for Perc cells installed at Fraunhofer ISE, thin film PV pilot lines installed at ZSW (CIGS) and HZB/PVKomB (CISGS) and Solliance (Organic/Perovskite PV), UTV-CHOSE (DSSC/Perovskite).

4.2 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
-*	CEA/INES	LabFab HET	c-Si Heterojunction pilot lne to validate the feasibility of HET cell mass manufacturing from both a technical and economical point of view. The line has a nominal capacity >15MWp/year, with all equipment provided by world-wide recognized suppliers	Le Bourget du Lac France | France
-*	ECN	R2R pilot for printed OPV/Perovskite PV	• Printing/coating and drying stations for R2R processing of Organic and Perovskite PV	Eindhoven | the Netherlands
-*	FhG ISE	PV-TEK pilot line for x-Si cells	•	Freiburg | Germany

-*	PVComB-HZB	Pilot lines for thin film PV	• complete R&D reference lines for 30 x 30 cm² solar modules based on thin-film silicon CIGS as well as 5- and 6-inch silicon heterojunction cells. • It covers different technologies like the development of transparent and conductive oxides (TCO's), contacts and barrier layers or laser-based interconnection technologies and state of the art analytics and modeling	Berlin | Germany
-*	ZSW	CIGS Pilot line	• ZSW is the record holder for the world's most efficient lab cell with 22.6% • Deposition of (transparent) conductive films, barrier films, and film layer systems on customer-specified substrates up to 30 cm x 40 cm, • In-line sputtering systems for substrates up to 30 x 30 cm2 • Experimental plants for sputtering, evaporation, and plasma CVD for substrates up to 10 x 10 cm2	Stuttgart | Germany
*	IMEC	IMEC-Silicon cell and module line	• Solar cell line for high-efficiency 156x156 mm2 monocrystalline silicon (PERC, PERT, IBC, SHJ-IBC) • Module line for assembly and testing of 60-cell silicon modules with focus on implementing novel materials and interconnection technologies	Leuven and Genk in Belgium
36	UTV	UTV-Centre for Hybrid and Organic Solar Energy (CHOSE)	• Sheet-to-sheet Pilot line production for DSSC up to 20x30 cm2 with lamination process • Sheet-to-sheet Pilot Line production of Perovskite modules (up do 20x20 cm2) and panels	Rome | Italy

*These infrastructures are not already included in CHEETAH KEAP catalogue

4.3 Recommendations

In order to fulfill the ambitions of the SET plan regarding manufacturing and installations, it was already stated in the SOPHIA report that to reach a common understanding of the current situation regarding pilot lines, a review of the current individual initiatives within the PV sector in the development of research pilot lines should be made, resulting either from bilateral agreement within a research centre and a private company, or from the public funding of a public/private consortium within a member state. Which technology, which parts of the value chain, which type of public funding, how the IP issues are solved, etc. This will help the community in developing the right future actions in Europe regarding PV pilot lines.

5 Facilities performance and lifetime assessment of modules and systems

The subtopics decribed in this section are in line with the R&I activies No.1 (PV for BIPV and similar applications), N°2, N°3 and N°4 (Operation and diagnosis of photovoltaic plants).

5.1 Cell and Module Electrical Performance

In terms of research infrastructure, this area can be sub-divided into: a) solar simulators and b) outdoor performance test stands

For an accurate performance assessment across the spectrum of existing and emerging PV technologies as mentioned in section 2, the future solar simulators should fulfil all the demands related to the specific properties of the various PV technologies:

- **Simulators** are needed that allow better control of a range of factors, be it diffuse/direct ratio, spectrum, intensity and duration. Other needs include capabilities for measurement of angle of incidence effects and for model developers, simulators to measure at low illumination levels and elevated temperatures.
- **Long flash simulators** are needed that can reliably deliver flashes >100 ms and combine the advantages of standard flashers (low power consumption even for full-size modules) with illumination times that are long enough to ensure that capacitive effects are minimised and/or that samples are stabilised before characterisation measurements.
- **Large area continuous solar simulator**: the current technology for characterising modules based on materials that rapidly reach and lose their light soaked state is the continuous solar simulator. Europe has a number of continuous simulators capable of handling full-size modules varying from Class AAA to CCC specifications. Large area

continuous solar simulators can simultaneously be used for pre-light soaking, accelerated lifetime testing (continuous light soaking), and hot spot testing.

LED based solar simulators are good candidates for small and large area sized cells and modules to provide a wide range of illumination without altering the illumination spectrum and are are expected to play a major role in future for quality assurance in manufacturing and in research because of the flexibility they offer in spectral tuning and their scalability.

5.1.1 Available Cheetah/EERA Infrastructure

INFRA#	Organization	Short name Infra	Description	Location
6	AIT	AIT-Indoor and Outdoor PV module performance test facility	Infrastructure utilized for • I-V curves measuremen • Precise power • determination at STC. • Improvements in performance, power and aging behavior by multiple R&D-methods.	Wien | Austria
51	CENER	CENER-Photovoltaic Cells and Photovoltaic Systems	• Characterization of photovoltaic cells and materials	Sarriguren | Spain
11	CIEMAT	CIEMAT-PV System	• Calibration and characterization of PV Cells and Modules.	Madrid | Spain
10	CRES KAPE	CRES KAPE-Photovoltaic Systems and Distributed Generation Department (PSDGD)	• Laboratory for PV component PV systems and distributed generation	Pikermi/Athens | Greece
14	DTU	DTU-Characterisation Laboratory for Organic Photovoltaics (CLOP	• Full set of testing equipment for the performance and energy output	Roskilde | Denmark
61	ENEA	ENEA-PV system and application lab	• PV demo sites	Portici(NA) | Italy

57	ENEA	ENEA-PV Smart Laboratory	• Characterization and testing of PV modules in indoor/outdoor operation	Portici(NA) | Italy
37	FHG	FHG-ISE PV Module-TEC	• Development of photovoltaic module technologies. • Analytical methods to characterize PV module prototypes and processes	Freiburg | Germany
30	JRC	JRC-European Solar Test Installation (ESTI)	• Large area solar simulators, also for continuous operation up to 8 hours • Research Infrastucture for the development of energy yield and rating methods for emerging PV technologies	Ispra | Italy
9	LNEG	LNEG-PV technologies lab	• Tests on solar thermal collectors and other solar components. • Solar Thermal, Solar Photovoltaic, Thermal Storage • Accredited Laboratory by IPAC according to NP EN ISO/IEC 17025:2005	Lisboa | Portugal
12	LU CREST	LU CREST-Module perfomance lab	• Module Performance Measurements • Power & Energy Measurements	Loughborough | United Kingdom
59	TECNALIA	TECNALIA-PV Module LAB	• Laboratory for PV Module Manufacturing and testing	San Sebastián | Spain
54	TUBITAK	TUBITAK - Marmara Research Center, Fotonic Technologies Laboratory	• Infrastructure for the characterization of photovoltaic cell and modules.	Gebze, Kocaeli | Turkey

43	UPM	UPM-CPV Lab test	• Indoor/outdoors studies on CPV components (solar cells, module, optical element) in standard test and under different operating conditions • different uniform/non uniform concentrated light , spectrum, and operative temperature	Madrid | Spain
52	UPM	UPM-PV system quality control facilities	• Testing, monitoring, failure detection and modelling of PV plants	Madrid | spain

5.1.2 Recommendations

Efforts are needed to improve the accuracy and repeatability of solar simulator systems for cell and and module performance measurement, in particular:

- Solar simulators that allow better control of a range of factors, be it diffuse/direct ratio, spectrum, intensity and duration.
- Capabilities for measurement of angle of incidence effects and for model developers, simulators to measure at illumination levels down to 0.1 W/m^2 for precise determination of equivalent circuit parameters with the variable illumination method which gives a deep understanding on the factors limiting the performance of the photovoltaic device.
- Better LED solar simulators, as a cost effective means to provide a wide range of illumination and spectral conditons, as well as illumination times that are long enough to ensure that capacitive effects are minimised and/or that samples are stablised before characterisation measurements.
- Infrastructure for testing under non-STC conditions

5.2 System Performance and Integration

Research on the optimization of electrical architecture and the advanced grid integration of PV power plants falls mainly in the field of electrical engineering research. However, these aspects are essential to high-penetration deployment of PV in the future, and are include here to ensure a holistic view of PV research infrastrucrture needs.

a) Utility-Scale Plants

Facilities are needed which allow research on systems that are of sufficient scale to be relevant to utility scale plants e.g. with a peak power in the range of the large commercial inverters. Aspects to be considered include operating voltage configurations (600V, 1000V, 1500V, 3000V, 5000V), massive installation of microinverters, lighting surge simulation, integrated MW scale electricity storage systems on DC or AC level, different grounding concepts and protection circuits, use of trackers, testing of grid support functions and scenarios, etc..

b) Centres for the testing of residential-scale systems

Such systems either form part of a ‘smart home’ or have functionality that would make them relevant to a ‘smart home’, and may have one or more of the following attributes:

- Modules with their own DC-DC MPP trackers (power optimizers) or DC-AC micro-inverters, the so called Module Level Power Electronics (MLPE).
- The ability to access local electricity storage (batteries) or deferrable loads (like a heat-pump, certain household appliances or an electric vehicle battery) or to offer services to the grid, for example frequency or active power regulation. These features are particularly interesting if a large portfolio is available in the same local grid.
- There should be the possibility to test different BIPV products, by means of suitable monitoring systems in order to evaluate not only active properties but also passive properties (indoor conditions).
- Capability to implement Demand Management strategies (DMS), including EV, thermal systems with heat pump, thermal storage using electricity. By extension, capability to tests different Energy management systems EMS and control algorithms at building level.
- Firmware that provides an interface (preferably using open source software) to a remote monitoring system.

5.2.1 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
-*	CEA/INES	MEGASOL platform		France
11	CIEMAT	CIEMAT-PV System	Calibration and characterization of PV Cells and Modules.	Madrid | Spain
61	ENEA	ENEA-PV system and application lab	• Distributed and cengtralized PV generation plants • CPV and Hybride Solar/Thermal application • Smart grid • BIPV & Ecobuildings design • PV demo sites	Portici(NA) | Italy
53	TECNALIA	TECNALIA-Facilities for BIPV systems	• Capabilities, facilities and equipment (SW, characterization devices) to offer services in the field of BIPV systems: ptical/mechanical/ thermal simulations • PV modules & devices characterization • Indoor and outdoor testing of BIPV modules and BOS, etc.	Donostia | Spain Derio | Spain
60	TECNALIA	TECNALIA-InGRID New Experimental Infrastructure for Smart Grids	• Advanced experimental infrastructure for the development, validation and commercialization of innovative products for renewable energies and smart grids.	Derio | Spain
59	TECNALIA	TECNALIA-PV Module LAB	• Laboratory for PV Module Manufacturing and testing	San Sebastián | Spain
52	UPM	UPM-PV system quality control facilities	• Testing, monitoring, failure detection and modelling of PV plants	Madrid | Spain
*	UPM	UPM-Magic box (Smart positive energy house)	• Distributed PV generation in Smart Grids environments	Madrid | Spain

*These infrastructures are not already included in CHEETAH KEAP catalogue

5.2.2 Recommendations

A system of joint usage of PV test sites (foreseen in the 2017 SET-Plan PV Implementation Plan) should be developed. This should include a unified and harmonized methodology to compare the performance of these systems. Flexibility and variety can be achieved by having access to the high number of different plants.

A dedicated MW-scale test platform open for European SMEs and industry partners to develop innovative concepts for modules, trackers and inverters, but also for demonstrating/validating diagnostic systems for advanced "made in Europe" products

Access to smart-home systems is needed – such systems should integrate both systems for electric tests (PV array simulators, grid simulator, loads), for remote control and telecommunications of smart homes actors, and monitoring and measurements systems. In such a way, it would be possible to test not only single subsystems, but also their integration into a smart macro-system, in which communications play a primary role.

5.3 PV durability

The aim should be to devise tests that allow lifetime guarantees in years to be offered to investors and operators. To do that it is necessary to drive deep into the detail of ageing mechanisms. Studying the effects of ageing at the macro-level (for example by looking at its impact on power degradation or module failure rate) is insufficient for further improvement of the modules, but seems to be the way to go for developing accelerated service life tests for testing labs, which do not know the composition of the modules and the potential aging mechanisms. The weathering stress and other stressors should be categorised for most expected climatic conditions and applications. Testing these stresses simultaneously as it occurs in reality requires the weathering in multi-stress climate chambers both of whole modules and of samples from modules (see subheading 'Indoor testing of performance degradation' under Module and system performance).

Failure modes and the processes that lead up to failure need to be understood and categorised for further development of more durable modules.

Potentially a large number of factors contribute to ageing and the effects of each need to be isolated. The international PV Quality Assurance Task Force is working in a coordinated way to disentangle ageing factors and identify tests to assure performance in diverse environmental conditions. Given the size and economic significance of the task, more resources are needed.

Condition monitoring is a related area of high interest for researches and for the operators. Characterisation using luminescence (EL, DLIT) and IV testing are being used, but further tools need to be developed. These tools include apparatus for characterisation of degradation in polymers e.g. Raman and luminescence spectroscopy and apparatus for characterisation of interfaces in the module e.g. SAM (scanning acoustic microscopy). The overall aim is to be able to identify degradation mechanisms and relate the rate of degradation to these mechanisms. This information will then be used to determine the suitability of a module for a specific climate and provide ideas for improving of the expected lifetime of the module. Further expansion of the capability of climate chambers, particularly to be able to perform combined stress tests e.g. damp-heat under illumination, are also desirable. These will allow a better correlation of the climate chamber results with expected degradation in the field. Suitable test procedures combining the natural stresses in an accelerated way have to be developed. The stress levels might be differentiated according to the intended application of the modules with respect to maximum temperature, temperature differences, ambient humidity, UV-radiation level, salt or other pollutants, system voltage. Results of field experiments using mobile outdoor testing equipment, laboratory artificial ageing and post mortem analyses and physical characterization methods have then to be combined and correlated regarding their time and temperature regimes to reveal the key failure modes and mechanisms.

5.3.1 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
51	CENER	CENER-Photovoltaic Cells and Photovoltaic Systems	• Characterization of photovoltaic cells and materials • Analysis and optimization of production technologies for solar cells • Development of photovoltaic cell technologies • Consulting in production environments of cells and photovoltaic components	Sarriguren | Spain

11	CIEMAT	CIEMAT-PV System	Accelerated Ageing of PV modules	Madrid | Spain
10	CRES KAPE	CRES KAPE-Photovoltaic Systems and Distributed Generation Department (PSDGD)	Laboratory for • PV component • PV systems and distributed generation	Pikermi/Athens | Greece
57	ENEA	ENEA-PV Smart Laboratory	• Characterization and testing of PV modules in indoor/outdoor operation	Portici(NA) | Italy
32	FHG	FHG-ISE Indoor/outdoor reliability Testing facility for PV modules	• Indoor investigation of the photodegradation of PV-modules exposed to UV irradiation under controlled environmental conditions Solar exposure in different ambient climate	Freiburg | Germany
30	JRC	JRC-European Solar Test Installation (ESTI)	• Climate chambers, UV chambers, EL and thermography, outdoor testing	Ispra | Italy
9	LNEG	LNEG-PV technologies lab	• Accredited Laboratory by IPAC according to NP EN ISO/IEC 17025:2005	Lisboa | Portugal
12	LU CREST	LU CREST-Module perfomance lab	• Module Performance Measurements • Power & Energy Measurements	Loughborough | United Kingdom
59	TECNALIA	TECNALIA-PV Module LAB	• Laboratory for PV Module Manufacturing and testing	San Sebastián | Spain
54	TUBITAK	TUBITAK - Marmara Research Center, Fotonic Technologies Laboratory	• Laboratory for the development and characterization of photovoltaic cell and modules.	Gebze, Kocaeli | Turkey
52	UPM	UPM-PV system quality control facilities	• Testing, monitoring, failure detection and modelling of PV plants	Madrid | Spain
*	ECN	ECN - indoor and outdoor characterization test labs	• Climate chambers, UV chambers, EL and thermography, outdoor testing	Petten | Netherlands

5.3.2 Recommendations

More infrastructure and best practices and procedures are needed to:

- Assess the stress climates seen by PV modules by detailled modelling of micro climates
- Model environmental stress dependent life-time energy yield
- Improve the understanding of the correlation of durability and key material properties
- Establish new accelerated testing routines that perform multi-stress testing instead of the current single-stress testing routines
- Assess the state of materials and performance by means of novel non-destructive module-scale metrology
- Monitor early field failures using mobile test outdoor equipment
- Go from deterministic to statistical reliability engineering (i.e. provide the data for statistical assessments and developing better warranties and thus reduce overall risk)

In order to realize this, there is a distinct advantage to do joint experimentation among several reserach laboratories: reliability tests take a long time and need to probe different conditions, this is virtually impossible to do as a single laboratory.

5.4 Integrated and Multifunctional Applications

a) Building Integrated PV

There are a significant number of research laboratories in Europe and around the world currently active in BIPV, with extensive facilities for BIPV-related electrical and construction testing. This includes several outdoor facilities with test bench platforms. Experimental buildings are also available, being highly useful tools for the evaluation of BIPV products performance in representative and, at the same time controlled, operational conditions.

This research infrastructure however needs to evolve to address several challenges:

i) Coordinated pre-normative R&D to support the development of needed standards and norms. New standard or a group of standards structured around technical requirements or functions based on Construction Products Regulation rather than on mounting categories within the building would also be highly useful. This is one of the proposed approaches for a new IEC/ISO project team PT63092. A specific need would be the determination of the solar factor of semi-transparent BIPV modules, which is a key parameter to be determined from the design stage of an architectural project. However there is also a need to optimise the number of required tests and test conditions in order to get a meaningful and complete characterization within reasonable resources and time frame.

ii) Assessment of new technological developments (new cell technologies, innovative interconnection systems, large area products, light weight products, flexible products etc.)

iii) Durability of the BIPV system and its components in the building context, including the effect of radiation exposure, higher module temperatures, water tightness, effect of module interconnections, etc.

b) PV in Transport

Electric vehicles are set to make an increasing impact on our transportation system. To optimise performance and in particular range, many manufacturers are considering integration of PV in suitable surfaces. The IEA PVPS programme is currently considering setting up a dedicated task on this topic.

Appropriate performance testing facilities will be needed for assessing actual components. For instance, 2016 EU specification for use of PV on fossil fuels cars requires electrical performance testing of full roof elements, so facilities of appropriate scale are required. Facilities to address eventual design type approval requirements may be required, as these are likely to be different from those for static modules in terms of loads, reliability and durability requirements.

c) Infrastructure Integrated PV (I2PV)

A number of infrastructure-integrated (bifacial) PV applications are being developed, notably for road surfaces and/or as noise barriers along railways and highways. Noise barriers along roads and rails provide ideal surfaces for photovoltaic systems without consumingadditional land. Appropriate performance testing facilities will be needed for assessing actual components.

d) Low-light energy harvesting

The development of the Internet-of-things (IOT) requires the use of energy harvesters. New generation of low cost thin-film PV, such as DSSC and Perovskites, permit to achieve up to (and more) 15 µW/cm2 for an indoor (200 Lux) illumination. This power density is enough for many of the typical IOT applications. Considering the rapid development of IOT this sector will be an important market case for PV

5.4.1 Available Cheetah/EERA Infrastructure

CHEETAH INFRA#	Organization	Short name Infra	Description	Location
-*	CEA		• Development of test procedures for BIPV system performance measurements • BIPV component development • Ten BIPV roof test benches supporting 35 m 2 (tilt between 0 to 50° • PASSYS test Cells test cells allow to perform research on façade component (including BIPV components)	Le Bourget du Lac France | France
61	ENEA	ENEA-PV system and application lab	• Distributed and cengtralized PV generation plants • BIPV & Ecobuildings design • PV demo sites	Portici(NA) | Italy
53	TECNALIA	TECNALIA-Facilities for BIPV systems	• Capabilities, facilities and equipment (SW, characterization devices) to offer services in the field of BIPV systems: optical/mechanical/thermal simulations • PV modules & devices characterization • indoor and outdoor testing of BIPV modules and BOS, etc.	Donostia | Spain Derio | Spain
40	TECNALIA	TECNALIA-KUBIK	Full scale test facility for the BIPV components characterisation under real conditions of use	Donostia San Sebastián| Spain
-*	UPM	UPM-Magic box (Smart positive energy house)	Distributed PV generation in Smart Grids environments	Madrid | Spain

36	UTV	UTV-Centre for Hybrid and Organic Solar Energy (CHOSE)	DSSC for BIPV. Developped Pilot Line for glass facede company (laminated panels up to 1 sqm) Outdoor characterization of BIPV components	Rome | Italy

*These infrastructures are not already included in CHEETAH KEAP catalogue

5.4.2 Recommendations

For BIPV, the existing range of research infrastructure should be reinforced to address challenges relating to a) performane and durability of innovative products and integration concepts, and b) development of a adequate and cost-effective system of standards and qualification procdures for BIPV products conceptsas part of requirements for structure safety and overall energy performance.

Facilities should be developed for assessing the performance and durability of PV component for integrated transport applications (PV for cars) and for infrastructure applications such as roads.

6 Quality Infrastructure

Quality or the assurance of quality is key to the continued development of PV and its emerging role as a major player in electricity supply. The 2017 IRENA report[1] " Boosting Solar PV Markets: The Role of Quality Infrastructure" identified the following key dimensions to quality issues:

- STANDARDS: defining methods and specifications
- CERTIFICATION: Meeting requirements of standards
- TESTING PROCESSES: Verifying conformity by testing
- ACCREDITATION: Evaluating conformity assessment bodies
- INSPECTION BODIES: Conformance with requirements
- METROLOGY: Determining conformance by measuring
- MARKET SURVEILLANCE : Monitoring market status

[1] IRENA (2017), Boosting Solar PV Markets: The Role of Quality Infrastructure, International Renewable Energy Agency, Abu Dhabi.

Research is also highly relevant for improving and innovating the quality infrastructure, in particular in relation to standards and to metrology. These and the foreseen needs in terms of R&D infrastructure are outlined below.

6.1 Standards and Pre-Normative R&D

Standards are an effective means of cementing the benefits of innovation and promoting the development of an open market. These are complemented by a range of characterisation measurements which may be applied to the final product or a component at an intermediate stage of the overall production process. Some of these are standardised, while for others a consensus "best practice" approach is adopted.

Over the last years the PV community, the International Electrotechnical Commission's TC-82, has built up a comprehensive body of standards addressing for PV devices and systems. Indeed the Cheetah project's survey on "Priorities for Standards and Best Practices" found that a sizeable majority (74%) of respondents from EU R&D community and from industry consider the current status of standards for PV to be "satisfactory, but with scope for improvement and/or new initiatives", and just 9% replied "unsatisfactory, important issues need to be addressed".

This underlines the need for R&D and industrial organisations to continue to work together to drive forward the adaptation and improvement of standards for new technologies, working through the relevant standards organisations. They also need to ensure that the characterisation techniques which are not standardised but nevertheless have a critical role to play in R&D or product development, are applied following best practices. In this regard the Cheetah survey produced the following overall conclusions (also reflected in previous sections of this report):

- "Reliability degradation and lifetime" is seen as the main standards' priority for all components and indeed for systems. Many of the comments received echo the results of recent Cheetah D5.5 report "Benchmark Knowledge of the Quality and Reliability of PV Technology", which illustrates the complexity of this issue. In Europe there may be scope to better coordinate efforts and resources to ensure appropriate tools are available for high quality and innovative systems.
- Standards for building integrated products were also flagged by a significant number of respondents, highlighting issues such as system functionality and performance, compatibility with construction codes and the expense of frequent design re-certification.

- The issue of sustainability was identified as at least a medium priority across the thematic areas. This may well reflect the growing interest in green procurement and circular economy policies in the EU, as well as the upcoming Commission study on the application of Ecodesign directive to PV products (modules and inverters) and systems.
- Concerning innovative PV technologies, DSSC and perovskites were cited as examples where new standards on electrical performance and reliability are needed.
- For systems, the respondents clearly prioritised the areas "operational monitoring and degradation" and "power and/or energy performance".
- For new applications the respondents gave high priority to PV for electric vehicle and to "energy harvesting for autonomous devices".

6.2 Metrology

The capacity to define and accurately and reliability measure electrical performance parameters underpins the global PV business, currently worth almost €100 billion annually. Traditionally the focus has been on energy conversion efficiency and power measurement at STC (P_{max}), but there's been growing efforts to develop parameters reflecting energy yield.

The EMRP project Photoclass (2014-2016) involved Europe's principal metrology labs and other leading organisations to address issues such as:

- An energy-based metric for PV efficiency, using standardised environmental data-sets for Europe and beyond.
- Robust and improved characterisation methods (e.g. spectrally resolved angular dependency of the responsivity, low light performance, and temperature dependency).
- Reduced measurement uncertainty for the absolute measurement of the natural and simulator irradiation conditions, spectrally and angularly resolved and the upper limit of the measured wavelength will be extended from 1050 nm to 2000 nm.
- New reference devices for an accurate and traceable calibration process from the cell to the solar park.

Its follow up PV-ENERATE aims to provide the metrological infrastructure, techniques and guidance to accelerate time-to-market for emerging photovoltaics technologies, which have the potential to significantly reduce the cost of photovoltaic energy. It has two main objectives: Firstly, to improve the PV energy rating standards and secondly, to improve the measurement equipment and methodologies to enable precise measurements of the parameters required for the energy rating.

It is also noted that:

a) Europe maintains at least 2 independent traceability chains for irradiance: at PTP linked to the WPVS and at JRC linked to the World Radiometer Reference Group at the PMOD Centre in Davos.

b) Europe organisations coordinate the annual International SpectroRadiometer Comparison (ISRC), which targets the harmonization of good practices in measurement and instruments traceable calibration procedures for solar spectra and irradiance measurements within the PV community.

7 Conclusions and Recommendations

PV has emerged as one of the key sources of clean energy at global scale. It stands out from other renewable technologies in terms both of the broad range of technology options and of the scope to significantly improve energy conversion efficiency in the coming years. European R&D now more than ever needs to coordinate its efforts to maintain its leading position at global level and to continue to provide the basis for a strong European PV industry and commercial sector.

Taking advantage of the broad experience of the 35 R&D organisation taking part in the Cheetah project, this report describes four main categories of research infrastructures related to the development of the full value chain of photovoltaics. Within these categories a number of subtopics are listed, with a description of background and current trends, an overview of existing RI within the Cheetah/EERA PV consortium and reommendations for the future per subtopic. It also address the role of Quality Infrastructure as an essential component in the continued development of PV.

For an efficient use of all the individual research infrastructure listed in this report, there might be oppportunities to create virtual research infrastructure networks in Europe where several research organizations can join forces to work on common topics in e.g. indoor/outdoor device characterization, reliability testing by sharing equipment and available skills and expertises. This type of networking will be very beneficial for a common and effective definition of the future European strategy on PV Research Infrastructures.

This report complements the recently published SET-Plan implementation plan for PV, produced by the Temporary Working Group comprising representatives of the EU Member States, industry, the research sector and academia. This implementation plan describes in general terms the (non-) technological R&D activities needed to achieve the overall strategic targets as defined in the SET plan Declaration of Intent.

This report is targeted at public and private funding agencies who make decisions on the allocation of research budgets. Where appropriate the Research infrastructure agenda should be taken up by ESFRI (European Strategy Forum on Research Infrastructure) in next updates of its roadmap), with a view to set up a whole range of multi-purpose RI, addressing the whole PV value chain form the lab to the fab all along the TRL scale. It should further enable flexible cooperation and optimal use by European user communities.

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[i] SET-Plan Declaration on Strategic Targets in the context of an Initiative for Global Leadership in Photovoltaics (PV), Strategic Energy Technologies Information System (SETIS), https://setis.ec.europa.eu

[ii] Based to some extent on the ITRPV roadmap – 8th edition 2017: http://www.itrpv.net/