



## **Priority Research Programme on Technologies for Advanced Energy Systems (TASE)**

Jean-François Guillemoles, Philippe Azais, Nicolas Retiere, Guillaume Ravel

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**Programme et Equipements  
Prioritaires de recherche sur  
Les Technologies Avancées des Systèmes  
Energétiques (TASE)**

***Priority Research Programme on  
Technologies for Advanced Energy  
Systems (TASE)***

**Strategic Plan**

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## EXECUTIVE SUMMARY

The transformation of a fossil-fueled into a carbon-free energy society is urgent in view of the climate challenges. Increasing the electrification of uses and the diversity of energy vectors (electricity, renewable gas, heat) are important means to decarbonize the energy mix and reach net-zero by 2050. The massive integration of renewable energies into the electricity system (photovoltaics, wind turbines) and the development of flexibility to guarantee the supply-demand balance at every moment are key challenges for the future. It requires some important changes of the transmission (especially for off-shore wind turbines) and distribution networks at the more local scales, technological developments in renewable production, economic, strengthening environmental and societal analysis to achieve a sustainable transformation.

This PEPR aims to provide and accelerate the deployment of innovative solutions for the integration of very high efficiency photovoltaics (**PV-Tec**) and floating offshore windfarms in networks that must become flexible and resilient (**Sys-Tec**). The environmental, economic, social and technological consequences of the energy system transformation must also be understood and measured.

PEPR's objectives are to carry out TRL 1 to 4 research and strengthen fundamental knowledge along three axes: integration and appropriation of renewable energy sources, anticipation of the energy system trajectory and development of breakthrough technological solutions. The massive integration of renewable energies also addresses the energy transition in societal and environmental terms. Hence, research must be conducted to understand the issues related to social transformations and societal appropriation (**Int.1**). And, the massive deployment of renewable energies cannot be achieved without providing relevant elements on the environmental impacts (**Int.2**).

The raising complexity of the energy system (more coupling between energy vectors, massive share of intermittent and variable energy sources, more local stakeholders...) requires the development of appropriate multi-scale modelling (from components to systems, **Ant.1**.) to anticipate the supervision and management at various scales (**Ant.2**.) This complexity could also weaken the energy system. Answers must therefore be designed to cope with extreme events, such as weather events and increase the system resilience (**Ant.3**).

Finally, the technologies (networks and photovoltaics) will be able to meet the challenges if they are economically accessible, environmentally acceptable (and accepted), limit the use of strategic or critical materials, provide support for national sovereignty and have the potential of upstream industrial development at the end of PEPR. Breakthrough technological innovation on networks will focus on the definition of new MVDC (Medium Voltage Direct Current) network architectures and power electronics converters for a massive integration of renewable sources and DC loads. (**Sys-Tec.1**). In addition, for the energy system to be controllable at various scales, research must be carried out on the digitalization of networks, taking into account massive and distributed data processing (**Sys-Tec.2**). For photovoltaic technologies, Silicon-only-based devices reach their limit in terms of efficiency and recycling. New cell technologies need to emerge with very high efficiencies and environmentally friendliness (**PV-Tec. 1**), while carrying a potential for industrialization in France or Europe. At the expected deployment level, it is particularly important to pay attention to the recyclability and eco-design of the modules (**PV-Tec. 2**). Finally, in order to have a chance to reach high TRLs, these new PV technologies must be able to demonstrate a very good operating life over time. This point is addressed by an approach combining modelling and advanced characterizations (**PV-Tec.3**).

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Have been consulted in the making of this document

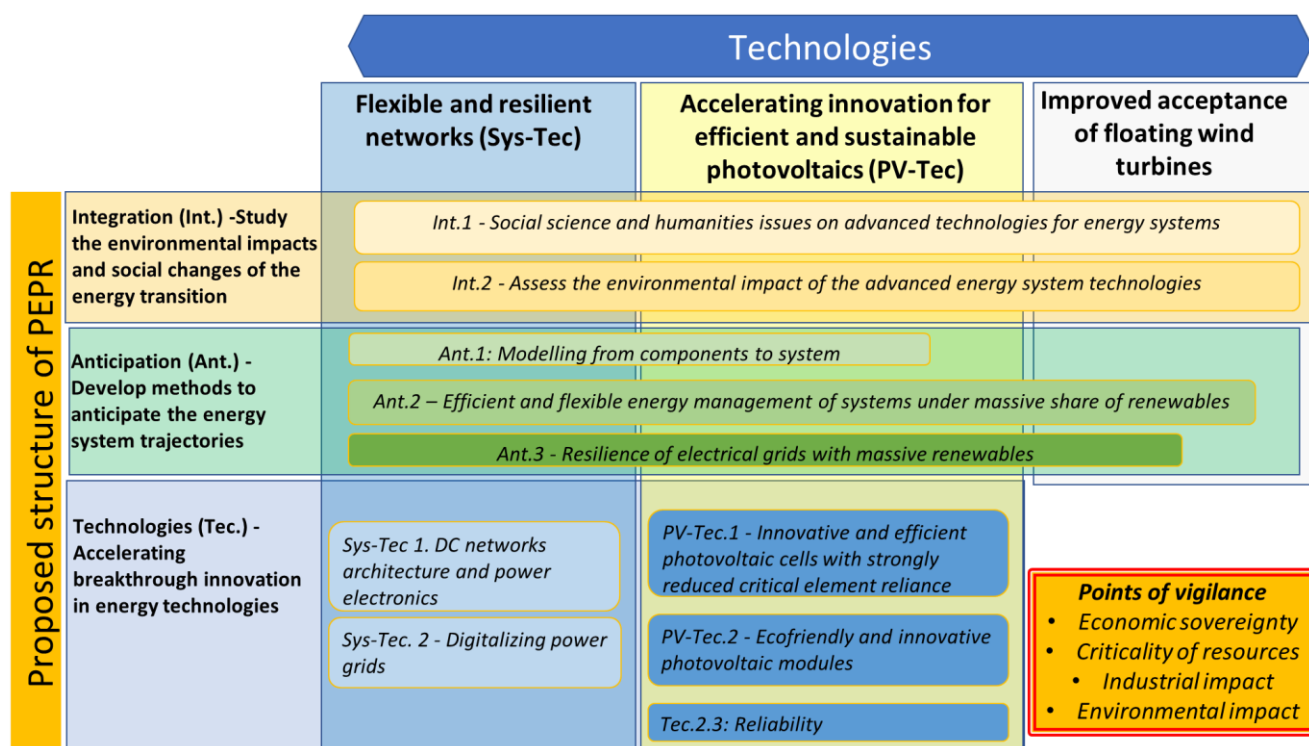
**Public Research Organisms:** France Universités, CGE, CDEFI, UDICE, CEREMA, INRIA,

**Institutes for the Energy Transition (ITE):** FEM, SUPERGRID, INES.2S, IPVF

**PEPR (National Strategy Research Programmes):** Batteries, Hydrogène décarboné, Recyclage, Décarbonation de l'industrie, 5G, Cloud, Electronique.

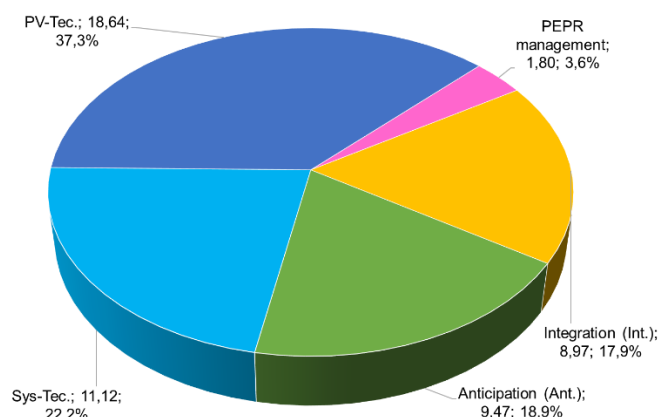
**Industrial R&D:** CSF-NSE

## PEPR AT A GLANCE



Structure of the topics addressed in the PEPR

	Action	budget allocation (M€)
PEPR Management		1,80
Int.1	CEI1	4,29
Int.2	CP1	4,67
Ant.1	TP1	1,89
Ant.2	CP2	5,05
Ant.3	CEI2	2,53
Sys-Tec.1	TP2	6,06
Sys-Tec.2	TP3	1,89
Sys-Tec.2	CP3	3,16
PV-Tec.1	CP4	1,52
PV-Tec.1	TP4	5,76
PV-Tec.2	CEI3	1,43
PV-Tec.2	CEI4	1,50
PV-Tec.2	TP5	3,39
PV-Tec.3	CEI5	5,05
	total	49,999



Budget and actions (TP = Targeted Project; CP: Call for Proposals; CEI: Call for Expression of Interest) and Budget breakdown by axis. Numbers are given in M€ and percentage figures refer to the total budget (50 M€).

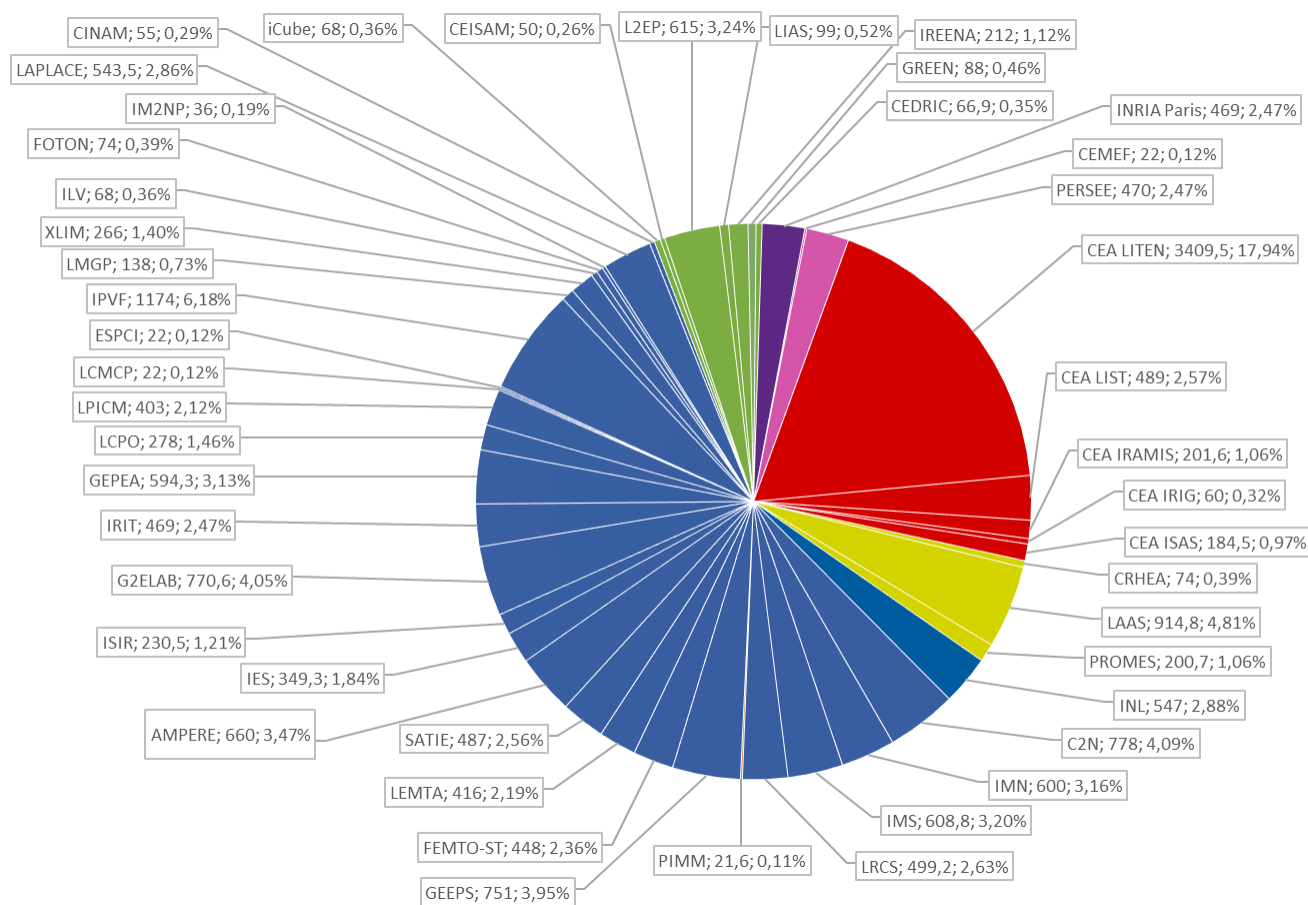
Action	budget allocation (%)
PEPR management	3,60%
Call for Proposals (CP)	28,80%
Call for Expression of Interest (CEI)	29,60%
Targeted Projects (TP)	38,00%

Summary of budget allocations according to PEPR actions.

Partner	CEA LITEN	CEA LIST	CEA IRAMIS	CEA ISAS	LAAS	INL	C2N	IMN	IMS	LRCS	GEEPS	FEMTO-ST	LEMTA	SATIE	AMPERE	IES
number of Ph-D	10	1	1	1	3	1	2	2	1	2	2	1	1	1	2	1
number of Post-Docs (eq. 12 months)	0	1,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Partner	ISIR	G2ELAB	IRIT	GEPEA	LCPO	IPVF	XLIM	LAPLACE	L2EP	INRIA Paris	PERSEE	TOTAL
number of Ph-D	1	2	2	1	1	4	1	2	2	2	2	52
number of Post-Docs (eq. 12 months)	0	0	2	4	0	0	0	0	0	0	0	7,5

*Requested Ph-D and Post-Docs in the targeted projects of the PEPR*



Financial resources by entity and type (blue : joint CNRS-University research unit, red : CEA, yellow: CNRS unit; dark purple: INRIA, green: university unit; pink: MinesParisTech unit)

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## 1 OUTLINE

The first part of this strategic document for the academic research actions briefly presents the National Strategy dedicated to advanced technologies for energy systems and gives the key elements of context.

In a second section, the PEPR framework is presented. This framework leads to a third part, which presents the strategic choices that have been made for the three research axes: integration and appropriation of the transformation of the energy system, anticipation of its trajectory and development of breakthrough technological solutions.

The proposed research actions, resulting from the strategic choices, are briefly presented in the fourth part. Their implementation is described in section 5.

A description of the operational management of the programme and its governance is proposed in section 6. The expected outcomes and the related KPIs of these actions are described in section 7.

This work has been drawn up taking into account the recommendations of several academic and industrial entities (sections 8 and 9).

To clarify the reading of the document, the detailed elements are gathered in the final annex section.

## 2 FRENCH STRATEGY ON TECHNOLOGIES FOR ADVANCED ENERGY SYSTEMS

### 2.1 Introduction

As part of the launch of “PIA 4” (“4<sup>ème</sup> Programme d’Investissements d’Avenir”)<sup>1</sup> and the “Strategies d’accélération” identified as priorities by the government, an interministerial task force was mandated by the executive committee (COMEX) on 29<sup>th</sup> January 2021 to draw up an acceleration strategy for “Technologies for Advanced Energy Systems” (TASE).

This strategy aims to promote the development of a French industry for new energy technologies capable of responding to the growing development of renewable energies and the electrification of uses. The acceleration strategy identifies three sectors with a strong potential for transforming French economy and society: photovoltaics, floating wind power and energy networks.

The strategy thus aims to develop an industrial sector based on French technological excellence, competitive at home and abroad, a vector for greater energy and industrial independence, job creation and a significant contribution to the energy and ecological transition.

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<sup>1</sup> <https://www.gouvernement.fr/4eme-programme-d-investissements-d-avenir-20-milliards-d-euros-pour-l-innovation-dont-plus-de-la>

## 2.2 Context

### 2.2.1 Towards a massive integration of Wind and Solar in the Grid

At the national level, the achievement of carbon neutrality by 2050 has been enshrined in law since 2019. The multi-annual energy program (“PPE” – “Programmation pluriannuelle de l’énergie”<sup>2</sup>) plans to significantly increase the share of renewable and recovered energy by 2028. In terms of grid-connected renewable energies, this means from 48.6 GW<sub>p</sub> (end 2017) to ~100 GW<sub>p</sub>, of which 35 to 44 GW<sub>p</sub> of PV and ~ 33 to 35 GW<sub>p</sub> of wind energy, including 5 to 6 GW<sub>p</sub> as floating wind turbines. It is thus envisaged that by this date, the installed capacity of renewable electricity will have doubled compared to 2017 (110 GW<sub>p</sub>), the production of renewable heat will have increased by 50% compared to 2016 and the share of biogas will be around 7% of overall gas consumption. Energy networks also cope with the development of new, decentralized and fluctuating renewable energy production methods, as well as changes in usage (increased electricity consumption linked to new uses, inclusion of electric vehicles). Faced with these major trends, the networks are now benefiting from recent and ongoing advances in communication technologies that enable energy systems to combine available energies and uses in a complementary manner. Based on these observations, it appears that a strengthened positioning on the markets of the most promising new energy technologies is becoming a fundamental issue of sovereignty for France and, more broadly, for Europe, and should allow for greater energy independence. Moreover, France's technological excellence in these fields provides to the country a definite advantage in developing an innovative, sustainable and internationally competitive energy industry capable of meeting the ambitions of the energy transition.

### 2.2.2 Where do we stand today?

According to the International Renewable Energy Agency (IRENA), new global renewable energy (RE) capacity, mainly driven by China and the United States, reached about 260 GW<sub>p</sub> in 2020 (Figure 1). It represents roughly more than 80% of all newly installed electricity capacities<sup>3</sup> in 2020.

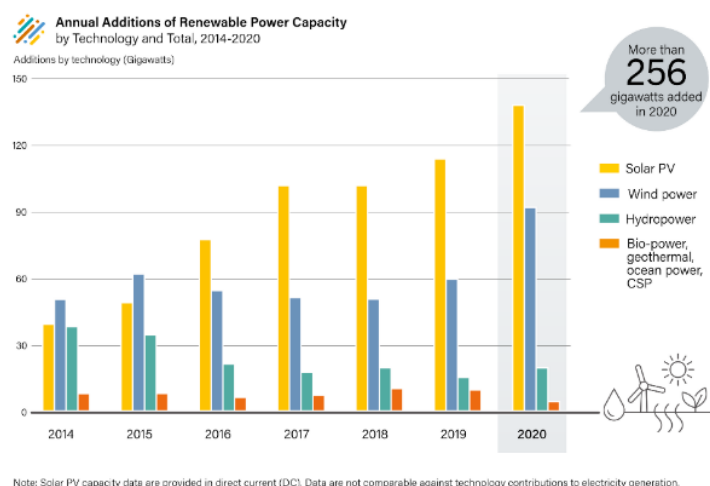
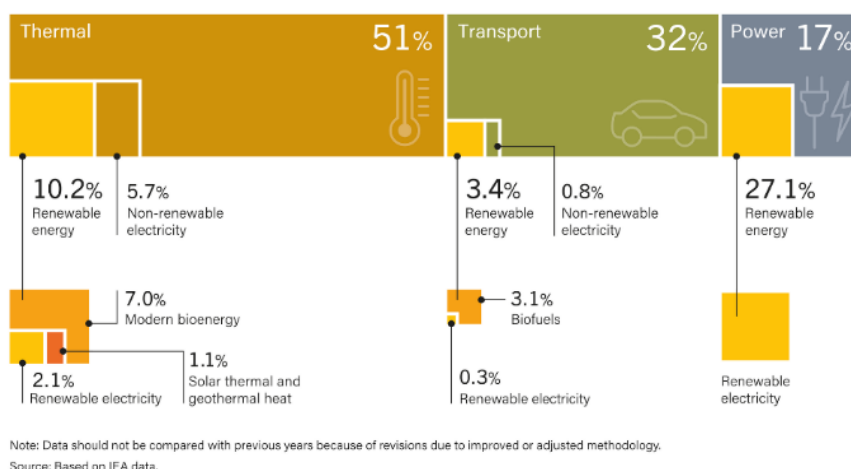


Figure 1 : annual additions of renewable power capacity by technology in the World (2014-2020).

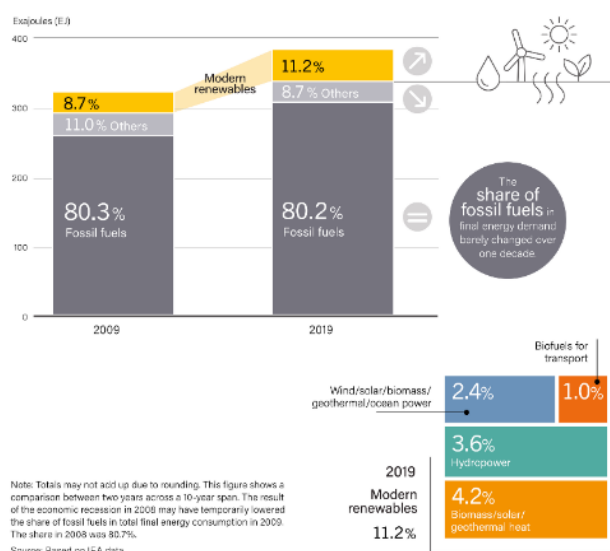
<sup>2</sup> <https://www.ecologie.gouv.fr/sites/default/files/20200422%20Programmation%20pluriannuelle%20de%20l%27e%CC%81nergie.pdf>

<sup>3</sup> [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA\\_RE\\_Capacity\\_Statistics\\_2021.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf)

While the increase in renewable energy installations is very strong, the share of renewable energy in final energy consumption is still low, regardless of the sector concerned (*Figure 2*). However, even if the growth of renewable energy is rapid, the installation of capacity using fossil energy consumption continues to grow at a similar rate (*Figure 3*).



*Figure 2 : renewable energy in total final energy consumption, by final energy use, in 2018 in the World.*



*Figure 3 : Estimated renewable share of total final energy consumption in 2009 and 2019.  
Details of renewable energy production in 2019*

Thus, the most important challenge is now to limit the consumption of fossil fuels that emit large amounts of GES but can be controlled by massively installing low-carbon renewable energy production at a price that is acceptable to the user and that provide the same service.

Europe has set itself the goal, as part of the Green Deal, of becoming the first carbon-neutral continent<sup>4</sup> by 2050. In December 2020, the heads of state and government of the European Union agreed to reduce greenhouse gas emissions by at least 55 % by 2030 compared to 1990 levels. In this context, renewable energy capacities in the European Union will have to

<sup>4</sup> <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52019DC0640>

grow very significantly over the next decade<sup>5</sup>. Their share of the overall energy mix, which is around 20 % in 2020<sup>6</sup> (Figure 4), could reach 32 % in 2030.

The TASE strategy is one of the element that should contribute to this acceleration in the deployment of renewable energy. This document gives the research program associated to the strategy.

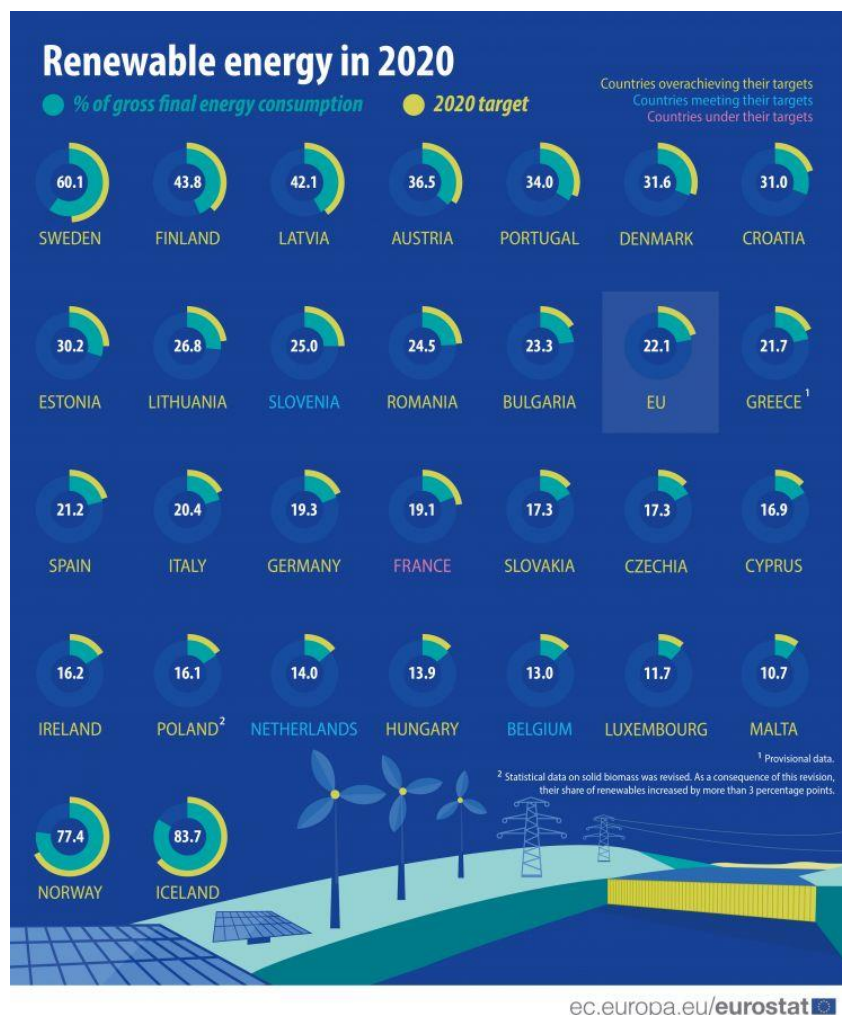


Figure 4 : in 2020, renewable energy represented 22.1 % of energy consumed in the EU, around 2 percentage points above the 2020 target of 20 %. France is just below the target.

### 2.2.3 Organization of the French R&D

In NROs (national research organizations) the research is carried out either in universities, engineering schools or National entities such as CNRS, CEA, INRIA, IFREMER, INRAE, CEREMA, ..., each of which with a specific domain.

<sup>5</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>6</sup> [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable\\_energy\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics)



According to a survey made by CNRS<sup>7</sup>, over 1000 FTE research staff are working in CNRS joint units on Renewable energy, and on which 500 FTE are working on Photovoltaic energy, and another 500 FTE are involved in transverse research topics that include energy transport and distribution networks.

French NRO's R&D on Energy is coordinated by entities like ANCRE, structured in working groups gathering all NROs involved in energy research. Some of these groups contributed to their expertise to the TASE PEPR' strategy.

CNRS research groups are also gathered into federative structures to foster collaborative research activities on a given scientific perimeter. Three CNRS' research federations specially contributed to the building of this program: FEDPV on photovoltaic issues, FEDESOL on solar energy and GDR SEEDS on electrical engineering. To these important groups, one should add other networks such as NANORGASOL, gathering molecular electronic researchers, and where a significant fraction is devoted to Organic PV, and the GDR SOLAR FUELS, where some research communities on photoactive materials, including PV ones, are present. Finally, there are also international research networks, such as CNRS@CREATE and SYNERGIES<sup>8</sup> that gather scientists from France and Singapore on energy networks and photovoltaics, NextPV<sup>9</sup> and LN2 that create opportunities on photovoltaics research between France and Japan or Canada, respectively.

Additionally, to the NROs activities, R&D of the industry and of the private sector should also be mentioned, For Instance EDF has several Departments carrying out R&D on various aspects of PV solar energy, as e.g. the STEP department in the Saclay R&D center, as well as on electricity networks. TOTAL, Schneider Electric, RTE also have corporate R&D.

Finally, public-private partnerships in the form of Institutes for Energy Transition (ITE) have been created under the impulsion of the Investment Plans for the Future (PIA) since 2012. They have the mission to help the transfer from low TRL R&D to industry. Two of them are devoted to Photovoltaics (IPVF and INES2S), one on Marine energies (FEM) and another one on transport of electricity (SUPERGRID).

#### 2.2.4 International benchmark

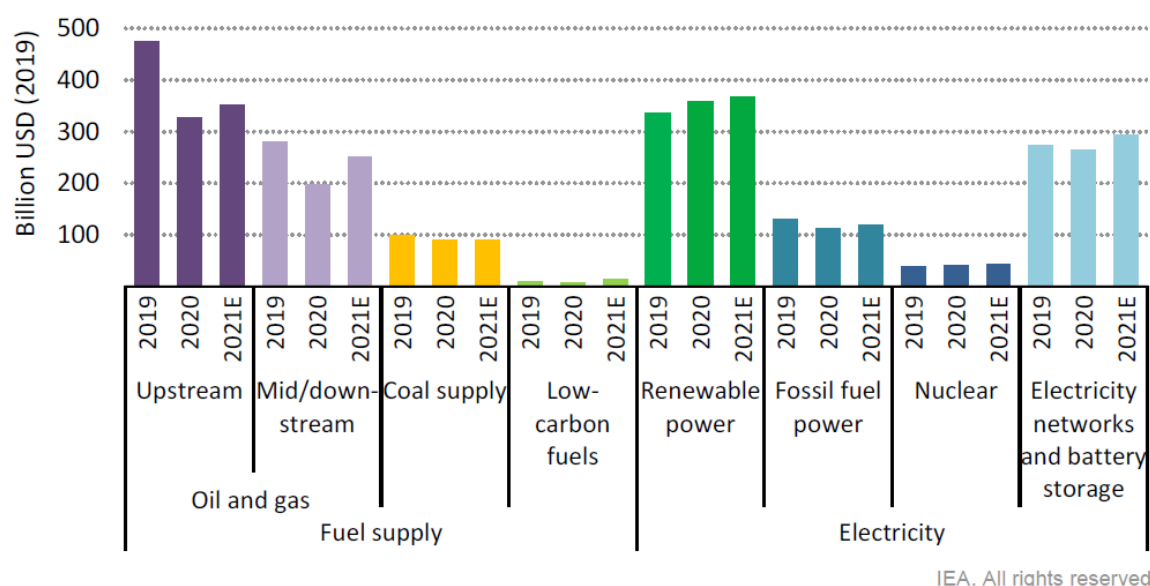
TASE strategy is part of the global effort on Low-Carbon Energy. World investment in Energy are led by the electricity sector and the increasing investments in renewables, networks and storage (*Figure 5*).

<sup>7</sup> Enquête Cellule Energie, 2021

<sup>8</sup> <https://www.celluleenergie.cnrs.fr/french-singaporean-network-on-renewable-energies/>

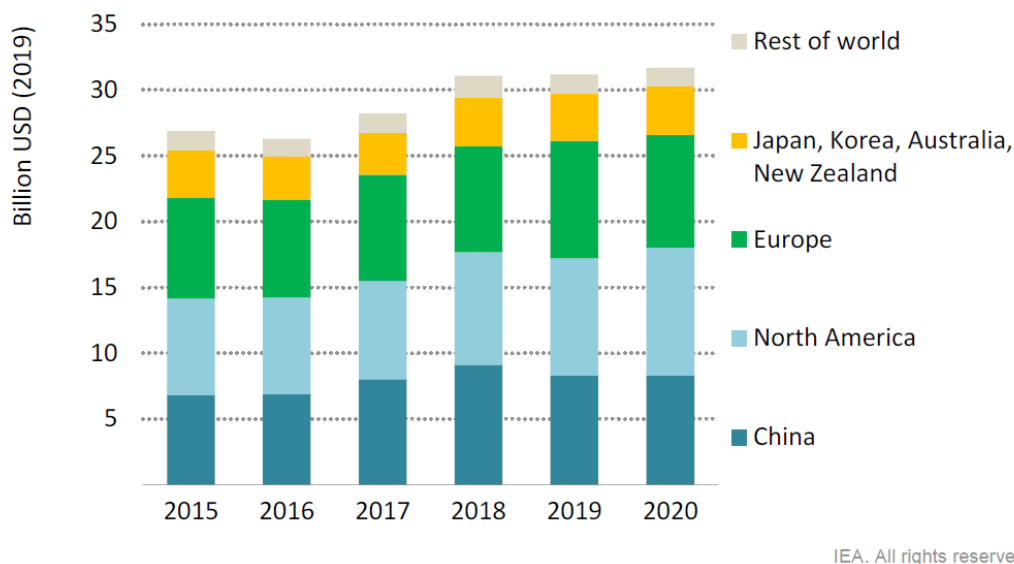
<sup>9</sup> <https://nextpv.cnrs.fr/>

## Global energy supply investment by sector

Figure 5 : Global energy supply investment by sector<sup>10</sup>

Despite the 2020 disruption caused by COVID-19, the investment in Renewable Energy remained solid in 2020. A decrease was observed for grids and storage investment but a slight rise is expected in 2021, especially in Europe and China. The investment in public R&D in the field has continued its rise in 2020, led by the research on Low-Carbon Energy. Its share in public R&D spending on renewables was 77% in 2015 and is now 83% in 2020. USA and Canada have seen a growth of their R&D budget while the European Commission budget allowed to the calls in 2020 slightly decreased (Figure 6 and Figure 7).

## Spending on energy R&amp;D by national governments

Figure 6 : Investment in public R&D<sup>11</sup>

<sup>10</sup> World Energy Sector Investment 2021, IEA.

<sup>11</sup> World Energy Sector Investment 2021, IEA.



If we look at French public investment in R&D, they are dominated by Nuclear Power and New Technologies for Energy (NTE). The share dedicated to fundamental research is one of the smallest but is kept constant along the years. The spending in NTE increased a lot in 2020 by 32% (Figure 8). On the share of the new technologies of energy, Energy efficiency is 257 M€, Hydrogen technologies, CCS, energy storage is 145 M€, and renewable energies 189 M€, of which 76 M€ is solar (mostly photovoltaic) and wind 15 M€. Electricity is 30 M€. The present research program is therefore a significant contribution to the strengthening and acceleration of fundamental research on renewable energy and networks.

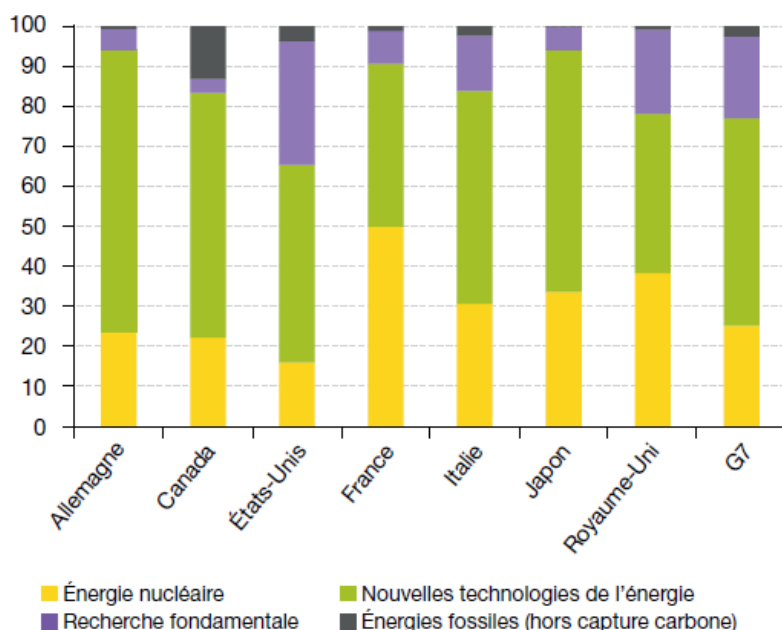


Figure 7 : Public spending in R&D of the G7 countries (yellow=nuclear power / green = NTE / purple = fundamental research / dark purple = fossil energies)<sup>12</sup>

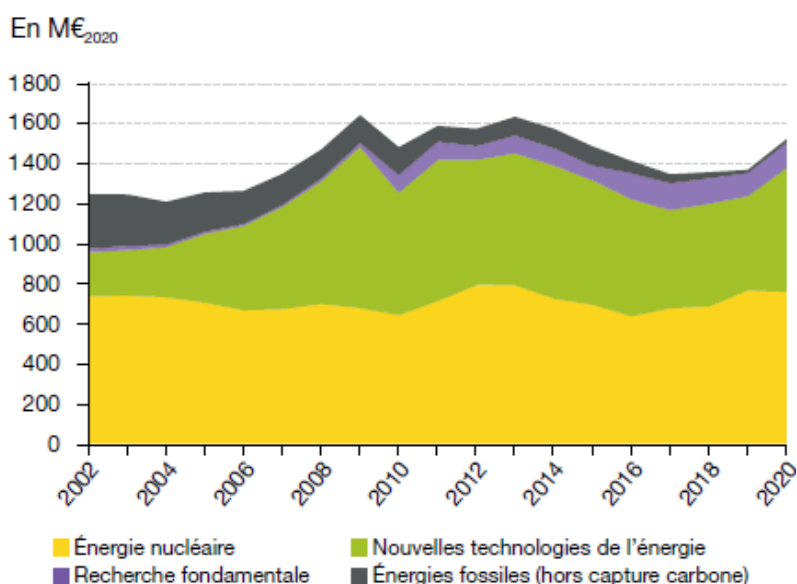
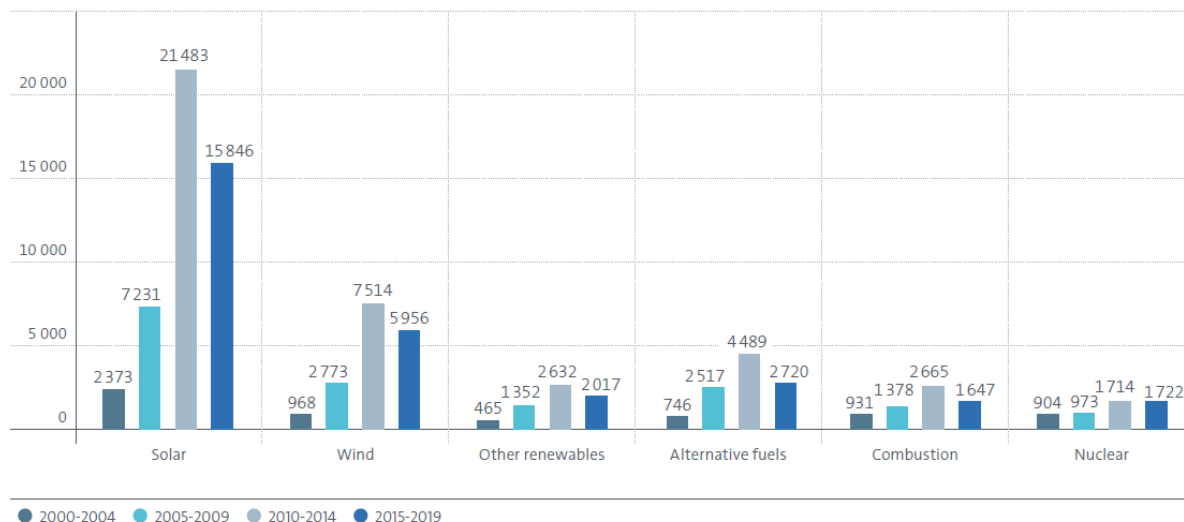


Figure 8 : Annual variations of the French public spending in R&D (yellow=nuclear power / green = NTE / purple = fundamental research / dark purple = fossil energies)<sup>13</sup>

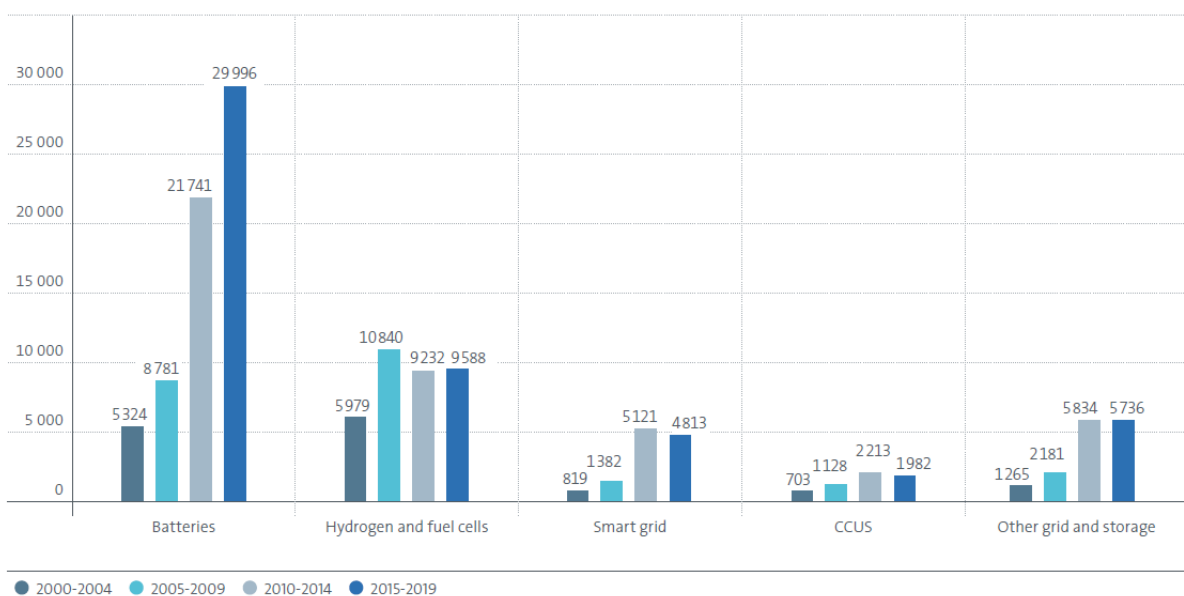
<sup>12</sup> Les dépenses publiques de R&D en énergie en 2020, Oct. 2021, MTE (France)

<sup>13</sup> Les dépenses publiques de R&D en énergie en 2020, Oct. 2021, MTE (France)

The main technology trends can also be seen through the patenting activity. They are dominated for the Low-Carbon Energy technologies by Solar and Batteries. Over the same period, there is slight rise of patenting activity for smart grids technologies (*Figure 9*).



*Figure 9 : Growth of International Patent Families in Energy Supply Technologies<sup>14</sup>*



*Figure 10 : Growth of International Patent Families in Enabling Technologies*

The Top 15 research entities that contribute to patenting activity are listed below (*Figure 11*). They include CEA and CNRS.

Some other important research institutes at World level are not given in this list: EPRI, NREL, SANDIA or Argonne National labs in the USA, AIT in Austria, VTT in Finland, INESC Tech in Portugal, IREC in Spain... Private companies or energy operators also contribute to innovative R&D in the energy sector such as RTE, EDF R&D or Schneider Electrics in France, E.ON and Siemens in Germany, ABB research center in Sweden and VTT in Finland. There are also very important centers in Japan in the energy field, at the forefront of which AIST in Tsukuba, that

<sup>14</sup> Patents and the energy transition. Global trends in clean energy technology innovation, April 2021, IEA

is also active on all fields of TASE. Other important centers in Japan are the University of Tokyo and Tokyo Institute of Technology. Prominent R&D centers in Europe on PV also include: Fraunhofer ISE (D), IMEC (BE), TNO (H), ZSW (D), EPFL (CH), HZB (D), Jülich (D).

A focus is presented in Figure 12 on PV technologies patenting activities. These figures confirms that French RTO are well positioned in the research on renewable energies.

	Country	LCE IPFs	Share of IPFs in selected fields										
			Combustion	Alternative fuels	Nuclear	Solar	Batteries	CCUS	Hydrogen and fuel cells	Smart grid	Other enabling	Chemical and oil refining	ICT
CEA/Alternative Energies and Atomic Energy Commission	FR	1772	0.1%	0.2%	3.9%	0.9%	0.6%	0.0%	1.2%	0.1%	0.6%	0.2%	0.1%
Industrial Technology Research Institute	TW	846	0.1%	0.1%	0.0%	0.5%	0.2%	0.2%	0.3%	0.1%	0.2%	0.1%	0.2%
Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V.	DE	725	0.1%	0.2%	0.0%	0.6%	0.1%	0.0%	0.3%	0.1%	0.2%	0.2%	0.1%
IFP Energies Nouvelles/IFPEN	FR	721	0.8%	1.2%	0.0%	0.0%	0.0%	1.4%	0.1%	0.0%	0.2%	1.2%	0.0%
University of California	US	666	0.1%	0.8%	0.4%	0.3%	0.2%	0.6%	0.4%	0.1%	0.3%	0.3%	0.0%
Electronics and Telecommunications Research Institute	KR	626	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%	0.0%	0.5%	0.1%	0.0%	1.0%
CNRS/National Centre for Scientific Research	FR	594	0.0%	0.2%	0.1%	0.3%	0.2%	0.2%	0.3%	0.0%	0.2%	0.4%	0.0%
Tsinghua University	CN	569	0.1%	0.2%	0.3%	0.2%	0.4%	0.1%	0.2%	0.3%	0.3%	0.1%	0.0%
National Institute of Advanced Industrial Science and Technology	JP	455	0.0%	0.2%	0.0%	0.2%	0.3%	0.2%	0.2%	0.0%	0.1%	0.2%	0.0%
Battelle Memorial Institute	US	402	0.1%	0.3%	0.4%	0.0%	0.1%	0.5%	0.3%	0.2%	0.2%	0.3%	0.0%
Korea Institute of Science and Technology	KR	369	0.1%	0.2%	0.0%	0.2%	0.1%	0.1%	0.3%	0.0%	0.1%	0.2%	0.0%
Korea Advanced Institute of Science And Technology	KR	368	0.0%	0.1%	0.2%	0.1%	0.1%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%
Massachusetts Institute of Technology	US	363	0.1%	0.1%	0.1%	0.2%	0.1%	0.2%	0.2%	0.0%	0.1%	0.1%	0.0%
Korea Institute of Energy Research	KR	346	0.4%	0.1%	0.0%	0.2%	0.0%	1.1%	0.3%	0.0%	0.1%	0.2%	0.0%
Myong Ji University Industry Academia	KR	333	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.9%	0.6%	0.0%	0.0%
<b>Total 15 Top applicants</b>		<b>9 155</b>	<b>2.0%</b>	<b>3.9%</b>	<b>5.4%</b>	<b>4.1%</b>	<b>2.5%</b>	<b>4.8%</b>	<b>4.3%</b>	<b>2.4%</b>	<b>3.4%</b>	<b>3.6%</b>	<b>1.5%</b>

Note: specialisation is reported in terms of share of all IPFs in the selected field, only for fields in which one or more of the listed institutions have contributed at least 0.5% of all IPFs. Different colour codes are used to highlight IPF shares in the following ranges: >0%-0.5%; 0.5%-1%; 1%-2%; >2%.

Figure 11 : Share of IPFs in selected fields

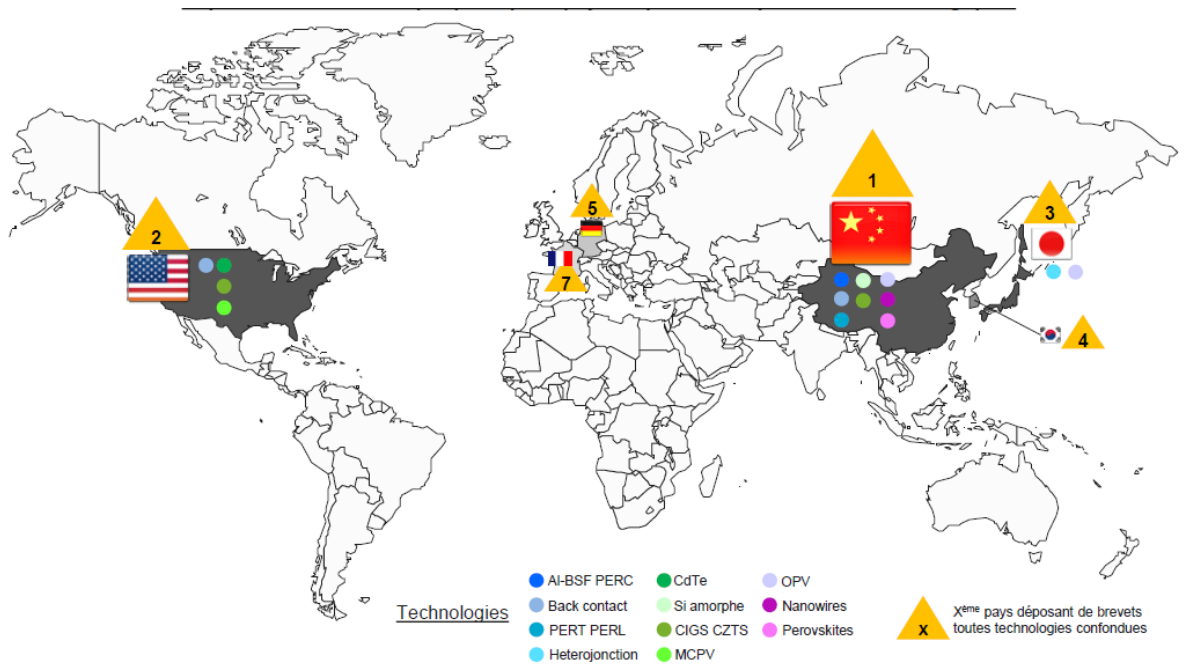


Figure 12: Distribution of patents by main priority countries and technological specificities. All technologies taken together, the three main areas for patenting are China, the USA and Japan (source: ANCRE CVT<sup>15</sup>).

## 2.3 Key challenges for acceleration

Three sectors demonstrating a strong potential for transformation of our economy and society and a capacity to become robust relays of economic growth for France have been selected in the framework of this strategy:

- Photovoltaics, which has very high growth forecasts for the next decade and a strong R&D potential;
- Floating wind energy, which is a promising emerging market, for which France has strong technological know-how and significant development potential;
- Energy networks, which are going to undergo major transformations and for which France has world-renowned technological know-how.

### 2.3.1 Photovoltaics

Over the past decade, the photovoltaic sector has experienced considerable growth on a global scale<sup>16</sup>, with installed capacity increasing from 41 GW<sub>p</sub> in 2010 to over 710 GW<sub>p</sub> in 2020, i.e. +1700 %. New installed capacity is growing at a rate of around 15 % per year, reaching 127 GW<sub>p</sub> in 2020.

On a European scale<sup>17</sup>, this market is also experiencing rapid growth, which has been increasing since 2017 and stands at 23 GW<sub>p</sub> of new capacity installed in 2019, more than double the previous year. This strong dynamism brings installed capacity in Europe to 149 GW<sub>p</sub>, i.e. a quarter of the World's installed capacity, with projections of 370 GW<sub>p</sub> in 2030 and 1050 GW<sub>p</sub> in 2050. France has an installed capacity of 11.5 GW<sub>p</sub> at the beginning of 2021,

<sup>15</sup> <https://www.allianceenergie.fr/cvt-ancr-public-etude-potentiel-technologique-economique-filieres-pv-a-haut-rendement/>

<sup>16</sup> <https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021>

<sup>17</sup> [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable\\_energy\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics)

including 1 GW<sub>p</sub> of new capacity commissioned<sup>18</sup> in 2020. Growth forecasts for installed capacity worldwide remain very high for the next few years and could reach up to 1000 GW<sub>p</sub> of new capacity by 2024, bringing the total connected capacity to over 1600 GW<sub>p</sub>. This sector has experienced an extremely sharp reduction in costs, making this energy increasingly competitive on a growing number of markets for large installations: in terms of LCOE, costs are around 45 €/MWh in France<sup>19</sup>, and up to 10 to 20 €/MWh in certain regions of the world with a lot of sunshine. Some research works identify efficiency gains that are still possible. However, Europe and France are highly dependent on imports: the European photovoltaic cell and module industry accounts for only 2% of the world market.

In this context of massive deployment, photovoltaics represents an opportunity for the French industry, which can claim to be positioned on fast-growing markets, particularly in Europe, but also in countries that are beginning to develop their industries. Thus, at the European level, EIT InnoEnergy and Solar Power Europe are leading the initiative of a European Solar Alliance with the aim of re-establishing a solid European PV supply chain and offering qualified and sustainable employment opportunities.

The development of the French industrial sector will also depend on its ability to innovate and position itself on its domestic market. In France, the Multiannual Energy Program (PPE) forecasts significant growth in the domestic market (currently produced mainly in Asia) by 2028, which should reach almost 3 GW<sub>p</sub> per year over the next few years.

Until now, industrial players in the manufacturing part of the sector have mainly concentrated their activity on encapsulating photovoltaic modules using imported cells. However, the first interesting deployments in the higher added value markets show interesting perspectives (production of ingots and cells, integration into buildings by solar tiles, agrivoltaics to combine solar and agricultural production, floating solar) and new generations of high efficiency cells with interesting first results by research centers which will remain to be confirmed with a reduction in costs. There is also a number of equipment or raw material suppliers (Arkema, St Gobain...). Most of the companies today are positioned downstream, in the Photovoltaic installation and PV power plant operation and maintenance, with some international scale players (EDF, TotalEnergies, Engie...). The insufficient level of production in France and even in Europe is a threat for these global players, in the competition with companies that are more vertically integrated and have secure a supply for the large-scale plants being built.

Cell technologies, which are still dominated by silicon, are evolving very rapidly. Current commercial efficiencies are above 20 %, but in the lab, efficiencies above 26%, close to the theoretical limits, have been demonstrated on wafer size. Innovations relating to cell passivation and heterojunction technology are currently ramping up<sup>20</sup>. Other innovations relate to silicon ingot and wafer manufacturing technologies (mono-cast silicon). In addition, these new approaches use manufacturing processes with a much smaller carbon footprint than current standards. By 2025-2030, tandem cells (for which France has a considerable lead in upstream research, notably with the ITE IPVF) using different materials in combination with silicon could also become widespread and be destined to win a significant market share. All of these innovations aim at improving the efficiency of the cells, which is a key factor in the profitability of the projects, due to the reduction in the costs associated with the installation (land, modules, structures, cabling, etc.). Technical developments are also taking place at the level of module design, with a tendency to seek better bifaciality, to increase the size of cells,

<sup>18</sup> <https://www.statistiques.developpement-durable.gouv.fr/chiffres-cles-des-energies-renouvelables-edition-2021>

<sup>19</sup> Report "Projected Costs of Generating Electricity 2020" International Energy Agency et Nuclear Energy Agency, December 2020. <https://www.iea.org/reports/projected-costs-of-generating-electricity-2020>

<sup>20</sup> <https://www.enelgreenpower.com/countries/europe/Italy/3SUN-factory>

to use half-cells, and in general, to implement all the innovations that make it possible to increase the unit power of modules.

As efficiencies goes up and cost goes down, markets opens and the production increases to the point that TW scale of installed capacity will be within reach in one or 2 years from now. This growth raises several issues. The first is that to find available space to install new PV power plants can become difficult, all the more as they tend to cluster first in the most favorable areas. There is then a need to improve integration in various spaces, and preferentially already artificialized spaces. Another integration challenge is also the variability of production, which becomes an issue at the grid level when the share of PV is high in the energy mix. The third issue is sustainability: with current technology, albeit lower than many other forms of electricity production, there are still CO<sub>2</sub> emissions in the manufacturing process that could be cut down, a dependence on critical materials (such as Ag and In) and a recyclability of PV modules that leads to down-cycling, as most of the value of the components cannot be recovered. Existing infrastructures in France<sup>21</sup> need therefore to be further developed.

France's capacity to innovate in the field of high value-added cells and modules, thanks to a world-renowned R&D ecosystem (in particular its Institutes for Energy Transition IPVF and INES2S, as well as the major research organizations CEA and CNRS), constitutes the foundation on which a French photovoltaic industry of international dimension can be built.

In addition to the design and manufacture of photovoltaic modules, the future development of the sector will also involve industrial issues relating to the manufacture of inverters, which are becoming increasingly important due to the integration within them of control and command systems for managing storage systems and, more generally, energy management. The other components of the panel, notably the glass and the frame, are also growth segments.

Finally, the development of innovative French solutions such as building integration, technical solutions dedicated to agrivoltaics, floating photovoltaics, photovoltaics on flexible substrates or design, supervision and predictive maintenance tools, will also represent new industrial challenges and could constitute tools for international differentiation.

Thus, the means deployed within the framework of TASE strategy must allow:

- The perpetuation and strengthening of French excellence in R&D, particularly in the fields of energy, physics, electronics and materials;
- The development of innovations generating a differentiating French offer with a low environmental footprint, while ensuring the effectiveness of technology transfer and its domestic economic spin-offs;
- The further development of the PV panel recycling sector, with a higher added value.
- The emergence of a French and European vertically integrated industry for the production of PV cells and modules capable of competing with international players, particularly Asian ones, on the national, European and world markets, and the emergence of an industry for other components such as glass or frames;
- Access to the market for specific innovations, particularly those developed by start-ups and innovative SMEs;
- The development of job-creating activities on the territory beyond installation and operation of PV power plants;
- The strengthening of national and European sovereignty in terms of energy production;

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<sup>21</sup> <https://www.soren.eco/>



### 2.3.2 Floating wind turbine

On 19 November 2020, the European Commission published its long-term strategy for offshore wind energy. While there is currently only 12 GW<sub>p</sub> of installed capacity on the coasts of the European Member States (the vast majority of which is land-based wind), the objectives put forward are ambitious: 60 GW<sub>p</sub> of offshore wind should be installed by 2030 and 300 GW<sub>p</sub> by 2050. Due to depth and spatial constraints, a significant part of this capacity will be installed using floating technologies. The costs of wind power have fallen sharply in recent years, from 200 €/MWh to around 45 €/MWh, thanks to R&D and industrialization efforts (increasing the nominal power of turbines, improving components, developing efficient production chains, etc.), to the scale effects of wind farms, and to feedback from the first farms installed. Some wind farms in Europe are now allocated without subsidies on the electricity sold, and with royalties that can be substantial.

The large-scale deployment of offshore wind technology in France and worldwide will require the development of floating wind, a technology that will allow the installation of wind turbines in areas further from the coast, thus making it possible to benefit from a greater wind resource.

Floating wind power is still at a pre-commercial development stage but several factors point to a major boom in the period 2020-2030:

- A fall in production costs which should be more rapid than that which has taken place in land-based wind, notably due to rapid growth in turbine size and greater confidence in the technology;
- The opening up of large areas for offshore wind energy development due to the removal of the depth barrier. While the development of land-based wind power has been carried out almost exclusively in the North Sea, the potential for floating wind power is much greater and can be found from the French and Californian coasts to the Japanese coast, via the Mediterranean Sea.
- An international desire to reduce greenhouse gas emissions and the recognition that offshore wind is an effective and relatively inexpensive way (for floating wind, we will have to wait for costs to decrease, but the electricity produced by wind power is already below market prices) to produce electricity.

This strong development of floating wind energy will lead to a race for industrialization, giving many French companies the opportunity to diversify their historical activities (oil&gas, marine construction, developers/energy companies, etc.). Thanks to the four pilot farm projects already financed by the French government and the allocation of the first commercial floating wind farms planned for 2022 and 2023, France is one of the most advanced countries in the commercial floating wind energy race. However, it remains to translate the lead in terms of projects into an industrial lead. The European offshore wind industry, notably Siemens Gamesa Renewable Energy and Vestas, are leaders in their fields and their production plants are mainly located in Europe. In this context, France has significant engineering and production capacities (460 companies positioned throughout the value chain) in many high value-added offshore wind segments: development and studies, nacelles<sup>22</sup> and blades<sup>23</sup>, electrical engineering<sup>24</sup> and cables. An integrated factory for blades and nacelles by Siemens Gamesa is also being finalized in Le Havre, which also hosts the construction site for the concrete gravity foundations of the Fécamp wind farm. In total, by the end of 2020, nearly 5,000 jobs were linked to marine renewable energy in France, mainly in the field of wind power. Between

<sup>22</sup> GE in Saint-Nazaire, <https://www.ge.com/news/press-releases/ge-renewable-energy-annonce-debut-production-eoliennes-haliade-saint-nazaire-emf-offshore>

<sup>23</sup> the GE-LM site in Cherbourg has notably manufactured what is currently the largest wind turbine blade in the World for *Haliade X*, <https://www.ge.com/news/press-releases/general-electric-inaugure-sa-nouvelle-usine-de-pales-eoliennes-a-cherbourg>

<sup>24</sup> Sub-station with Chantiers de l'Atlantique, <https://chantiers-atlantique.com/activites/energies-marines-ingenierie/>

2019 and 2020, with the launch and continuation of work on the Saint-Nazaire, Saint-Brieuc, Courseulles and Fécamp wind farms, the increase has been substantial, with a 59 % rise in one year.

In the field of floating wind turbines, France could become a key nation for the production of floats. Its expertise in naval architecture, construction and infrastructure<sup>25</sup> could be a lever for a whole chain of subcontractors. Northern European countries have shown with the wind turbine that the first-mover bonus is important. Today, no shipyard or port is able to meet the production rates required for the development of commercial wind farms: one or two floats weighing several thousand tons of steel or concrete will have to be built every week for almost a year for a 1 GW wind farm. Production capacity installed relatively early in France could supply the French market but also a growing global market. As it is relatively easy and cheap to transport floats over long distances, competition with Eastern Europe or Asian countries will be strong. However, the quality of the infrastructure can make the difference and the high investment costs would be amortized by high volumes, the creation of sustainable jobs and the generation of benefit for export projects.

The development of ports for the industrialization of floats and the installation of turbines at the quayside is also an interesting growth relay for ports, which are still very dependent on carbon-based activities such as the processing of coal or hydrocarbon cargoes. In parallel with these industrialization efforts, it is necessary to facilitate the acceptability of these projects by all stakeholders and users of the sea. In this respect, efforts must be made to promote the acquisition of environmental and technical knowledge of the identified sites and to enable the cohabitation of uses.

Thus, the development of a French floating wind energy industry, with the ambition of becoming a world leader, must respond to the following challenges:

- The reduction of the environmental impact of floating wind turbines and the development of co-use with other users of the maritime space, allowing the acceptance of these technologies to be reinforced;
- Ensuring society's acceptance of the sector;
- Consolidation of French offshore testing facilities in order to stimulate and facilitate experiments on marine renewable energy;
- Supporting the transition of local SME activities to the offshore wind energy markets;
- The implementation of programs aimed at improving and industrializing equipment for floating wind farms (second generation floats, development of more powerful turbines, direct current connection solutions, floating substations and dynamic electrical cables, underwater robotics and predictive maintenance, etc.);
- The development of technological bricks for industrial capacities and port infrastructures allowing the industrialization of float production and the installation of turbines at the quayside (lifting means, production, assembly, storage, launching and transport chains and methods);
- The dissemination of offshore standards adapted to floating wind energy technologies and the creation of mechanisms to promote European content;
- The development of initial and continuing training must respond to the expected increase in demand from this emerging sector.

There are many synergies between wind energy and floating wind energy, as these two technologies share a significant part of their benefit. This strategy proposes an orientation

<sup>25</sup> Chantiers de l'Atlantique, Louis Dreyfus Armateurs, Eiffage, Bouygues



resolutely turned towards the development of the floating wind, it will also be able to accompany projects supporting the synergies between these two technologies.

### 2.3.3 Energy networks

The turnover of electricity, gas, heat and cold will amount to 75 b€ in 2020 in France, including 21 b€ for network infrastructures. In the future, the essential decarbonisation of the French energy system will result in a strengthening of the weight of these network energies, in particular heat and electricity, for which certain uses, such as mobility, will intensify. This will require major investments (nearly 100 b€ for electricity networks alone by 2035). At the same time, the integration of more and more renewable sources into these networks (wind and photovoltaic for electricity, biogas for gas, biomass, geothermal or waste heat recovery for heating networks), coupled with the need to constantly balance injection and consumption on these networks, are sources of increasingly complex technical challenges.

As a result, energy networks will change significantly in the coming decades. To enable a secure and decarbonized energy supply while optimizing the total cost of the energy system, they will have to adapt to flexible production, integrate energy storage and coupling between energy fluids in order to absorb variations in the production of resources, and finally favor flexibility of demand. This requires a combination of energy system technologies and digital and communication technologies to effectively integrate the actions of the various users, operators, consumers and producers.

Lastly, the sociological and economic challenges linked to smart energy networks are just as important as the technological and regulatory aspects. Social characteristics (socialization process, family context, domestic context) and individual characteristics (knowledge of the energy mode, general scientific culture and ability to interpret energy data, personal motivations, proximity to Information and Communication Technologies), must be addressed to achieve a successful energy transition.

The French industrial sector combines major energy companies (EDF, ENGIE, etc.), equipment manufacturers among the international leaders (for electricity: Schneider Electric, Legrand, Sagemcom, Nexans, etc.), start-ups, numerous SMEs and ETIs, recognized research bodies (CEA, CNRS, Institutes for Energy Transition including Supergrid, France Energies Marines, IPVF, INES2S, etc.) and, possibly, new entrants from the world of ICT for example (ATOS Worldgrid...). The main electricity (RTE, Enedis) and gas (GRTgaz, Téréga, GRDF) network operators are among the largest in Europe. As major contractors, they play a key role in innovation by enabling industrial players to test their solutions on French networks and then industrialize them. The French network industry is thus present across the entire value chain (network equipment, energy storage, network management, ICT infrastructure, data processing, engineering and consulting). It will be able to stand out as a leader abroad by proposing a complementary or integrated offer. However, international competition, particularly from Asia, has developed considerably over the last twenty years and is penalizing the French industrial sector, which is generally oriented towards excellence. Recently, a return to greater quality seems to be taking place among network managers, including in developing countries, which should once again favor the French sector.

The size of the existing French network infrastructures and interconnections and the nature of its energy mix does not place the French energy system under strong constraints, unlike other regions of the world. This has so far only moderately favored the creation of significant economic models for the experimentation and development of innovative technologies.

However, in order to be able to export to international markets, the creation of industrial references on French networks remains crucial.

Thus, the sustainability and development of the French offer on the national and global markets requires:

- to pursue R&D and strengthen French industrial projects on key technological bricks;
- to facilitate the first industrial deployments of a sufficiently significant size to create credible references on the international market and support the export of French solutions;
- to promote the development of innovations and demonstrators adapted to non-interconnected areas and emerging markets, allowing interaction between networks and between energies, and integrating energy storage infrastructures and turnkey solutions;
- to develop and disseminate standards in terms of data, communication and flexibilities management, which are a prerequisite for lowering costs and accelerating innovation;
- to develop an initial and continuous training offer in line with the needs and ambitions of the sector.

## 2.4 Implementation of the TASE Strategy

The implementation of the strategy will mobilize €515 million of the 4<sup>th</sup> Plan of Investments for the future (PIA4 – “4<sup>ème</sup> Programme d’Investissements d’Avenir”). The PIA4 funding is spread across the entire innovation value chain:

- The establishment of a PEPR research program (Priority Research Equipment and Programs) for an amount of 50 million;
- Support for the maturation of innovative solutions brought by research actors and the consolidation of testing facilities, particularly in the marine renewable energy sector, for an amount of 35 million;
- Support for innovation, particularly targeting SMEs, and promoting the development of technological building blocks and demonstration activities for an amount of €250 million;
- This funding will be complemented by other budgetary measures dedicated to support the rapid development of the industrial capacities required for the production of RE.

## 3 SCOPE OF PEPR TASE

### 3.1 The mission

The French government has approved the implementation of a PEPR program in order to support research for the emergence of innovations in the fields of solar photovoltaic energy, floating wind power and for the emergence of flexible and resilient energy networks. The aim is to propose and develop breakthrough technologies in these fields to enable a strong increase of renewable energy connected to the network. This program includes a specific section to deal with the environmental impacts and social appropriation of new energy solutions.

The first feedback from large-scale renewable energy installations shows that the energy transition can only be achieved if the technological, economic (in the broadest sense of the term, both financial and environmental) and societal aspects are tackled in a concomitant manner and not in a totally separate way.

Key points that have been identified are:

- fostering innovation for efficient and eco-friendly photovoltaics
- fostering innovation for increased flexibility and resiliency in the energy system
- managing the increased complexity of the energy system
- preparing a transition that is truly green
- assessing the paradigm change for users and suppliers

Additionally, the strategy should serve re-industrialization and sovereignty plan ("France Relance"), with the goals to modernize the production system and decarbonize industry; (re)localize critical strategic activities and innovate, by supporting investments in research and development but also by preserving and developing skills.

The PEPR program should strengthen the capacity of public research to support the objectives of the national energy transition strategy in terms of increasing the share of renewable energy in the energy mix. It will do so by developing basic research in energy and preparing for technological breakthroughs (Technology Readiness Level - TRL 1 to 4) based on innovative technologies in the fields of energy networks, photovoltaics (PV) and floating wind power.

It should also scrutinize the conditions for an environmentally and socially desirable transition for the stakeholders, and especially the empowerment of social bodies, with low environmental impact and a reduced dependence on critical materials. The projects should finally be complementary to other tools focused on innovation and industrialization, which are part of national (PIA4) or European plans.

Finally, the program should ensure a transparent, neutral and high-quality governance.

Focusing on broader range is a contradiction in terms. The objective of the PEPR is clearly to narrow down research topics to have an impact on selected topics. Note that many aspects of decarbonization are also addressed in other PEPR (PEPR "décarbonation de l'industrie", "mobilité durable", "Solutions pour la ville durable et innovations territoriales", "batteries", "hydrogène").

For the specific case of PV cells and modules, indeed, the focus is (TP5, CEI 3 and CEI4) on enabling innovative uses of PV technologies, including precisely partially transparent PV, mouldable or flexible modules, through innovation in envelopes and packaging. The broader context of deployment will be partially addressed in CP1.

The broader energy efficiency is part of other actions.

### 3.2 Identification of types of action

There are three types of action in TASE's PEPR program:

- Targeted projects (TP). These projects bring together a well-defined community of recognized scientific and technical excellence, capable of working together on clearly identified issues, and be ready to start doing so immediately.

- Calls for Expressions of Interest (CEI). These calls aim to launch one or more projects within a rather well defined community capable of working together to address key issues, but where a process is needed to help forming the consortium.
- Calls for Proposals (CP). These calls address a more diffuse community that is able to organize itself to propose research projects on the topics of the call.

### 3.3 Budget structuring constraints and choices for the PEPR

The budget balance has been prepared taking into account:

- The mission statement and the national strategy. The TASE national strategy mentions that the humanities, social and environmental aspects must represent 10 M€ out of the 50 M€.
- The leading of the whole programme over the next 5 years should represent about 2 M€. This funding also includes a budgetary reserve to balance the themes during the launch of the Calls for Proposals (CP) and Calls for Expression of Interest (CEI), to target PhD grants that would be necessary to accelerate a specific topic during the course of the programme.
- The SGPI (General Secretariat for Investment, a central service of the French administration attached to the Prime Minister) and the MESRI (French Minister of Higher Education, Research and Innovation) recommend that the rate of targeted projects should not exceed 40 % of the budget.
- There was also an intention to distribute the budget for the network and photovoltaic topics evenly, considering their weight in the strategy.

## 4 SCIENTIFIC STRATEGY

In addition to the explicit demand expressed in the TASE strategy as shown in sections 2 and 3, we have used several criteria to guide the choice of the research topics that should: and

1. be able to have an impact around the end of the program (within 5/6 years)
2. nevertheless, be still relevant in the next decade, and be relatively robust to technology reorientations that are possible in the technologies that are not completely stabilized (as in network management and photovoltaic devices and modules)
3. be complementary to other research programs in the domain, and more specifically address challenges that have been overlooked or under-invested, so that the PEPR would have a strong impact in accelerating innovation
4. contribute to a better organization of the national public research, creating critical mass on crucial challenges, and impelling cross fertilization between hitherto separated fields of knowledge and innovation
5. contribute to position France as a leader of R&D in technologies for advanced energy systems.

## 4.1 Vision for the program

The PEPR addresses at the same time the socio-technical-economic challenges (axis “Integration”), the anticipation of the trajectory of the energy system with a massive integration of renewable energies (axis “Anticipation”) and finally some disruptive technological actions related to energy networks and solar photovoltaic (axis “Technologies”).

The structure of the PEPR is summarized in *Figure 13*.

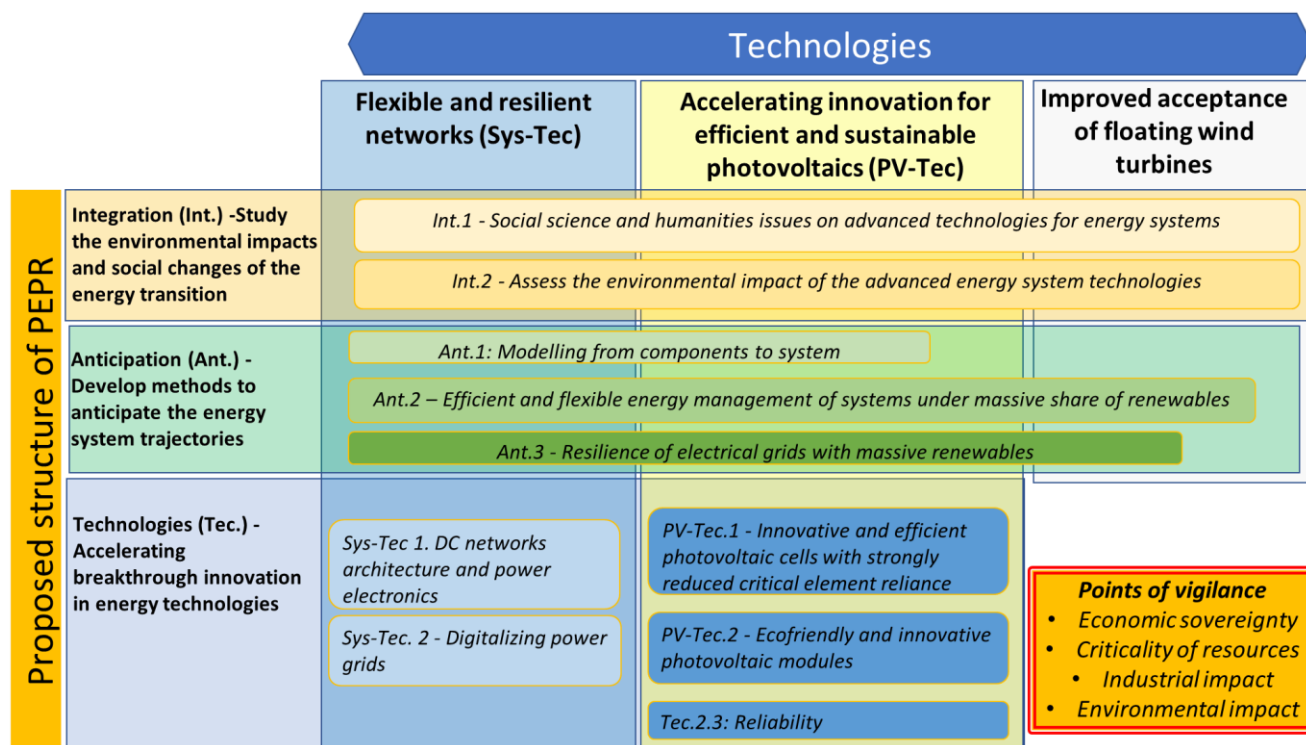


Figure 13 : structure of the topics addressed in the PEPR

It is worth noting that even if the National Strategy TASE does not ask for low-TRL research developments on floating wind turbines, wind generation is a significant part of the renewable energy production and will be considered in the Anticipation axis in the same way as PV production.

## 4.2 Study the environmental impacts and social changes of the energy transition (“Integration” - Int.)

The growing penetration of renewable energies "in many forms" (electricity, gas, heat, etc.) is considerably changing the energy landscape, with potentially strong impact on the society and the environment.

This research axis therefore focuses on the development of knowledge required by the advanced analysis of social and environmental impacts.

### 4.2.1 Int.1 - Social science and humanities issues on advanced technologies for energy systems

#### 4.2.1.1 Background and context

The transformation of the energy sector from fossil-based to zero-carbon implies technological innovations but also profound structural changes of energy systems from a social, economic,

spatial, and legal point of view<sup>26</sup>. The energy transition raises ethical and justice issues and the need for public debates on the technical, political, economic choices that would be possible for a fully effective transformation of the energy production, distribution and uses<sup>27</sup>. New forms of energy generation and uses emerge that require rethinking the articulation between generation, grids and energy uses at all spatial and time scales<sup>28</sup>. Some challenges are the integration of local energy communities, the articulation of the political choices, market design and regulations and their impacts on the energy balance, the role and limits of the end-users as actors, enabler of the energy transformation.

There is now a large body of disciplinary work on the relationships between energy, space, regulation and society in the context of climate change and carbon neutrality aim. In particular, this research axis addresses the diverse issues of the analysis of the deployment of new energy technologies and redesign of energy systems: sociotechnical regime and deployment niches of innovative technologies have been broadly explored notably in western -completely electrified – countries<sup>29</sup>. Social scholars agree on the profound reorganization of markets induced by the insertion of intermittent (notably flexibility) and dispersed (notably territorialization) renewable energies and the need to finely qualify emerging phenomena such as energy communities and microgrids, frugal uses, internet of energy, social mobilization, in order to adapt technologies and research & innovation policies (see in particular<sup>30</sup>).

#### 4.2.1.2 PEPR strategy

Our strategy aims to renew the analytical frameworks and models used by the human and social sciences to investigate the energy transformation. It should provide a multidisciplinary view able to understand and thus support the deployment of innovative technological projects in the fields of efficient photovoltaics, floating windfarms and grids. Our strategy fosters the mobilization of diverse research fields in sociology, geography, planning, urbanism and architecture, psychology, politics, economy or management sciences). It covers notions such as materiality, commons, resource potential, socio-energetic assemblage, technical-economic approaches or modelling, or normativity. The research works should contribute to de-compartmentalize knowledge by fostering practice analyzes and a continuous dialogue between engineers and researchers in humanities and social sciences.

This crucial topic will be addressed through a Call for Expression of Interests that will facilitate the emergence and the structuration of a multidisciplinary consortium with the required skills (see section 12.5.1 for the call description).

A main objective of CEI 1 is to better integrate desirability issues in the technological projects deployment, as such, it includes the acceptance issues mentioned. Expected results are about

<sup>26</sup> GIEC, 2018 : Résumé à l'intention des décideurs, Réchauffement planétaire de 1,5 °C, Rapport spécial du GIEC sur les conséquences d'un réchauffement planétaire de 1,5 °C par rapport aux niveaux préindustriels et les trajectoires associées d'émissions mondiales de gaz à effet de serre, dans le contexte du renforcement de la parade mondiale au changement climatique, du développement durable et de la lutte contre la pauvreté [Publié sous la direction de V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor et T. Waterfield]. Organisation météorologique mondiale, Genève, Suisse, 32 p.

<sup>27</sup> Valentine, SV, MA Brown, and BK Sovacool. Empowering the Great Energy Transition: Policy for a Low-Carbon Future (New York: Columbia University Press, 2019)

<sup>28</sup> Nadai, Alain ; Labussière, Olivier. 2018, Energy transitions. Palgrave Macmillian

<sup>29</sup> Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., Nykvist, B., Pel, B., Raven, R., Rohrer, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: State of the art and future directions, Environmental Innovation and Societal Transitions, 31, 1–32. doi: 10.1016/j.eist.2019.01.004.

<sup>30</sup> McCauley, D., Ramasar, V., Heffron, R. J., Sovacool, B. K., Mebratu, D. & Mundaca, L. 2019. Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. Applied Energy. 233-234, p. 916-921.



understanding and solving the conflicts between general public and technological projects owners. These conflicts may result from impacts on landscape and environment, individual behaviors. Governance, regulations, data management and projects implementation procedure are others examples of sources of conflicts.

CEI 1 is a call for expression of interest and the detailed definition of the expected results will be a part of the projects building itself. Furthermore, as funding is limited, it is essential that the consortia that will emerge will deal with key issues and are coordinated with each other in order to address complementary topics while limiting overlap.

## 4.2.2 Int.2 - Assess the environmental impact of the advanced energy system technologies

### 4.2.2.1 *Background and context*

The energy transition implies the massive deployment of innovative technologies. This can only be based on solutions whose environmental impact is under control. This implies the implementation of approaches that take into account the complete life cycle and the pursuit of R&D actions in environmental sciences that allow a better understanding of interactions with the environment. For example, the development of offshore wind energy in general and floating wind energy in particular will require a considerable increase in our knowledge of marine ecosystems in order to better understand the interactions of wind farms with their environment.

The environmental impacts of various systems of production and consumption have been studied for several decades by developing and applying life cycle assessment (LCA) with its own ISO standard. LCA studies depend on data of uneven quality and quantity<sup>31</sup>, assumptions and scenarios, as LCA assesses the real world in a simplified model. Assumptions and scenarios may vary from one study to the other, leading to different LCA results<sup>32</sup>. These variations in LCA approaches and results may be confusing, especially for non-experts so that, education and training is required to assist users in the application of LCA<sup>33</sup>. Going-from globally to regionally assessed environmental impacts is key to facilitate decision-making. The concept of regional LCA has emerged a decade ago<sup>34</sup> and based on only few recent LCA studies<sup>35</sup>, a sustainable energy development plan can be designed at regional scale. This approach needs to be further developed and expanded in order to address its dynamic (evolution with time) and systemic approach (from one technology to energy mix). In addition, LCA should not be misunderstood as a comprehensive or a complete assessment. The assessment of social sustainability, and its integration with economic and environmental sustainability, are still in the developmental stage and recent developments were initiated to broaden traditional environmental LCA to a more comprehensive Life Cycle Sustainability Analysis (LCSA). Further developments need to be conducted to integrate LCA with non-accounted environmental, societal (i.e. societal life cycle assessment SLCA<sup>36</sup>) and economic

<sup>31</sup> Guo M., Murphy R.J., 2012 : LCA data quality: Sensitivity and uncertainty analysis, *Science of The Total Environment*, 435-436, 230-243, doi:10.1016/j.scitotenv.2012.07.006.

<sup>32</sup> Qin Y., 2019 : Characterizing uncertainties in life cycle assessment. *UC Santa Barbara*. PhD dissertation. 123 pp., <https://escholarship.org/uc/item/99m421b1>

<sup>33</sup> Maastricht University organises an online LCA course: "Life Cycle Assessment: Basic Principles and Uses", <http://www.um-lca-course.nl>, developed and implemented within the framework of Chemelot InSciTe, with support of the Province of Limburg, the Netherlands

<sup>34</sup> Wegener Sleeswijk A., 2011 : Regional LCA in a global perspective. A basis for spatially differentiated environmental life cycle assessment. *Int J Life Cycle Assess*, 16, 106–112, doi:10.1007/s11367-010-0247-5

<sup>35</sup> Tabatabaie S.M.H. et al., 2018: A regional life cycle assessment and economic analysis of camelina biodiesel production in the Pacific Northwestern US. *Journal of Cleaner Production*, 172, 2389-2400, doi:10.1016/j.jclepro.2017.11.172.

<sup>36</sup> Hunkeler D., 2006: Societal LCA methodology and case study. *Int J Life Cycle Assessment*, 6, 371-382

impacts, and promote the use of LCSA for the cohesive achievement of the United Nations (UN) Sustainable Development Goals (SDGs) framework. Finally, new usage of energy systems have shown potential to minimize negative environmental impacts while maximizing positive environmental impacts. For instance, agrivoltaics (or agrophotovoltaics) has been developing as a way to simultaneously produce energy, reduce evaporation (through shadowing) and maximize crop yield and quality<sup>37,38</sup>. However, the benefit versus cost of agrivoltaics is difficult to assess, as it depends on the crop type, local hydrological cycle, solar radiation availability, so dedicated research is still needed<sup>39</sup>. Also new usage/applications of energy system (technology mix...) may be imagined to minimize the detrimental impacts on the environment and maximize the benefits.

#### 4.2.2.2 PEPR strategy

First, the methodology of data collection measuring the environmental impact is fragile on the strong assumptions that are made concerning the representativeness of the collected data and their interpretation. In this light, a critical review of existing methodologies and the proposal (and validation) of ways to improve them would certainly be more useful than funding the collection of data that is strongly suspected of being irrelevant.

Second, the LCA methodology, in particular on prospective aspects, remains largely to be developed. An important question in the framework of PEPR TASE is the impact in LCA of the extensive use of technologies studied in TASE (energy networks, PV and wind), with potential interaction effects (and competition) between the developments of the various technologies (ENR and networks), in particular on resources.

Particularly interesting cases of study are the implementation of floating wind turbines and PV, which are presumed to have positive externalities for the environment. An example that we have discussed is that of agrivoltaism, which could show positive externalities at the intersection of water use, food, energy and biodiversity. In addition, a new methodology for crossing cumulative impacts (positive and negative) with a multi-criteria parameterized approach (especially for modelling and simulation) should be investigated.

We propose a Call for Proposals to detect and fund the best proposals submitted by research groups consortium (see section 12.4.1 for the call description).

### 4.3 Develop methods to anticipate the energy system trajectories ("Anticipation" – Ant.)

As previously shown in the context section, the energy sector is undergoing changes, which have or will lead to major developments in the way energy networks (electricity, gas and heat) are planned and managed both in France and in Europe.

The anticipation of the energy system trajectories, the identification of emerging issues, potential threats, opportunities, the definition of operating scenarios require the development of methods for modelling the energy networks. These models will be crucial to optimize the

<sup>37</sup> Dinesh H. and Pearce J.M., 2016: *The potential of agrivoltaic systems. Renewable and Sustainable Energy Reviews*, 54, 299–308.

<sup>38</sup> Valle B. et al., 2017 : Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Applied Energy*, 206, 1495-1507, doi:10.1016/j.apenergy.2017.09.113.

<sup>39</sup> Toledo C., Scognamiglio A., 2021: Agrivoltaic systems design and assessment: a critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns). *Sustainability*, 13, 6871, doi:10.3390/su13126871



energy mix and the management of energy flows. The different spatial and temporal scales must be questioned through these anticipation approaches. An essential dimension of the anticipation axis is also the necessary integration of the collected data, being measured or synthesized, provided by industrial partners or labs. They document the impacts of choices of all kinds (social, economic, technical) on the system trajectory. They integrate the role of stakeholders in the energy transition process. However, they add a supplementary degree of complexity in the models that we want to develop.

In the anticipation axis, several challenges will be therefore addressed at low TRL levels:

- Development of multi scale models to represent with accuracy and parsimony the energy system from the components to the networks. It means simple models with great explanatory predictive power on various space and time scale, for various energy vectors – **Ant.1**
- Definition of advanced methods for the management of a massive share of renewable sources, highly dispersed and variable. A particular attention will be paid to the development of forecasting tools virtual power plants management methods – **Ant.2**
- Modelling and identification of the key levers to achieve resilience of future power grids with a massive share of renewables and therefore a higher sensitivity to extreme events and actions taken by decentralized actors – **Ant.3**

#### 4.3.1 Ant.1 - Modelling from components to system.

##### 4.3.1.1 Background and context

Cities consume two-third of world's total primary energy and emit 70 % of global carbon. Today, more than 50 % of the world's population live in urban areas and it is expected a proportion of 70 % by 2050<sup>40</sup>. Specific actions are therefore required to increase the energy efficiency of urban energy systems and the renewable rate. In this regards, Multi Energy Systems (MES) are seen as a promising technology by coupling the different energy carriers. MES may be a solution for reducing the negative impacts of the non-controllable intermittent renewable sources, a better management of mutual compensation effects between loads and storage capacities. They are at the heart of Power-to-X and X-to-Power technologies ...<sup>41,42</sup>. Because of their complexity, the enhanced integration of MES in cities will require the use of models to encompass the diversity of energy vectors, components and scales. These models will be used to design and operate optimal MES or to forecast what could be their potential advantages, including the large deployment of emerging technologies of energy sources (e.g. Perovskite-based PV panels) or new conversion components between energy networks.

There are various options for the modelling approaches depending of the objectives (simulation or optimization), the time resolution (from few milliseconds for control of power grids to several minutes for operation of heat networks) and the space resolution (building, district or city scales)<sup>43</sup>. Depending on the options, the mathematical approaches range from the physics-based simulation model to 100% artificial intelligence model. Actually, most of the

<sup>40</sup> IEA, Empowering Cities for a Net Zero Future : unlocking resilient, smart, sustainable urban energy systems, Report, July 2021.

<sup>41</sup> M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, 'Classification and challenges of bottom-up energy system models - A review', *Renewable and Sustainable Energy Reviews*, vol. 129, p. 109917, Sep. 2020, doi: 10.1016/j.rser.2020.109917

<sup>42</sup> G. Mavromatidis et al., 'Ten questions concerning modelling of distributed multi-energy systems', *Building and Environment*, vol. 165, p. 106372, Nov. 2019, doi: 10.1016/j.buildenv.2019.106372.

<sup>43</sup> C. Klemm and P. Vennemann, "Modelling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches," *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110206, Jan. 2021, doi: [10.1016/j.rser.2020.110206](https://doi.org/10.1016/j.rser.2020.110206).

existing approaches are now relying on co-simulation<sup>44,45</sup>. Nevertheless, they are costly in computing resources and their complexity limits the inclusion of data. Combining both physics-based simulation and AI techniques is also possible to obtain powerful models able to deal with the available data related to the description or the uses of the modeled system<sup>46,47</sup>. However, there are still very few applications doing that for MES and the existing tentative approaches are very restricted<sup>48</sup>.

#### 4.3.1.2 PEPR strategy

In TASE, we focus on the modelling at the district scale, the “natural” and central scale for the deployment and management of distribution energy networks. The modelling approach will be proposed not restricted to energy balance but able to represent the energy flows and the constraints they bring on the system. The model could be used to forecast the influence of some parameters or operational strategies on the system efficiency. It could also be embedded in an optimization loop to design optimal solutions. The time resolution will be between few seconds and several minutes. Instead of co-simulation, our program focus on hybrid methods able to combine physics-based models and AI-based methods. We expect from this hybridization to provide parsimonious models able to simulate with a reasonable time complex MES at the district scale. Our strategy wants also to develop reference benchmarks for the study of MES. These benchmarks are very common for power systems but there is no similar test system of MES publicly available for the French and international research community.

To accelerate the research works on this crucial issue and the further development of multienergy design tools, we propose a targeted project on this sub-axis, focused on a small research consortium with the required skills on multi energy systems and advanced hybrid modelling (see section 12.3.112.4.1 for the project description).

### 4.3.2 Ant.2 – Efficient and flexible energy management of systems under massive share of renewables

#### 4.3.2.1 Background and context

The massive integration of renewable energies into the energy mix will lead to a strong growth of distributed sources, with a lower predictability than controllable power plants. There are also more and more active loads and others sources of flexibility such as storage connected to the grid. Microgrids gather loads and renewable sources in a single controllable entity that can be used connected to the grid or in island mode to provide enhanced reliability and power quality<sup>49,50</sup>. Local energy community emerges to better integrate the renewable energy sources at a local scale<sup>51</sup>. The energy system is therefore becoming more and more localized. The localization trend is accompanied by diversification. Indeed, the variability of renewable energy sources and their intermittency require considering transfers/coupling between various energy vectors in order to balance the supply/demand of the entire energy system (addressing all the

<sup>44</sup> B. Leitner, E. Widl, W. Gawlik, and R. Hofmann, ‘Control assessment in coupled local district heating and electrical distribution grids: Model predictive control of electric booster heaters’, *Energy*, vol. 210, p. 118540, Nov. 2020, doi: 10.1016/j.energy.2020.118540.

<sup>45</sup> E. Widl et al., ‘Studying the potential of multi-carrier energy distribution grids: A holistic approach’, *Energy*, vol. 153, pp. 519–529, Jun. 2018, doi: 10.1016/j.energy.2018.04.047.

<sup>46</sup> L. von Rueden, S. Mayer, R. Sifa, C. Bauckhage, and J. Garcke, ‘Combining Machine Learning and Simulation to a Hybrid Modelling Approach: Current and Future Directions,’ in *Advances in Intelligent Data Analysis XVIII*, Cham, 2020, pp. 548–560. doi: 10.1007/978-3-030-44584-3\_43.

<sup>47</sup> [1] [2003.04919] Integrating Scientific Knowledge with Machine Learning for Engineering and Environmental Systems.” <https://arxiv.org/abs/2003.04919> (accessed Feb. 14, 2022).

<sup>48</sup> Qingsen Cai, XingQi Luo, Peng Wang, Chunyang Gao, Peiyu Zhao, Hybrid model-driven and data-driven control method based on machine learning algorithm in energy hub and application, *Applied Energy* Volume 305, 1 January 2022, 117913

<sup>49</sup> A. Hirsch, Y. Parag, and J. Guerrero, ‘Microgrids: A review of technologies, key drivers, and outstanding issues,’ *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 402–411, Jul. 2018, doi: 10.1016/j.rser.2018.03.040.

<sup>50</sup> F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, ‘Microgrids management,’ *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 54–65, May 2008, doi: [10.1109/MPE.2008.918702](https://doi.org/10.1109/MPE.2008.918702).

<sup>51</sup> R. Ford, C. Maidment, C. Vigurs, M. J. Fell, and M. Morris, ‘Smart Local Energy Systems (SLES): A framework for exploring transition, context, and impacts.’ *SocArXiv*, Jul. 31, 2019. doi: 10.31235/osf.io/j4d57.

energy needs, not just electricity). There is also a diversification of actors emerging along with the non-profit historic operators<sup>52</sup>.

Localization, variability and diversification are reshaping energy systems and a crucial issue is now: how can the whole system, and finally stakeholders and consumers, may benefit or suffer from these features. For instance, a disadvantage of a massive share of renewables is the decrease of the total inertia that may result in unstable operations. This brings new issues related to distributed control<sup>53</sup>. Generally speaking, new control schemes may enable the optimal use of local resources to maintain a balanced operation whatever the operating conditions are<sup>54,55,56</sup>. Advanced weather forecasting methods are also expected to be valuable for network management and market trading<sup>57</sup>.

#### 4.3.2.2 PEPR strategy

Our research strategy focus on advanced local control and forecast methods for the management of renewables, active loads and energy system. It aims to build a globalized energy system where global and local scales support each other, to the benefit of all actors. Three main research issues will therefore be addressed:

- How to increase the forecast quality by mixing the already used weather forecasts at regional scale and all the available local measures.
- How to manage multiscale and multi-temporal energy storage systems providing new services and addressing all the usage and energy vectors.
- How to control distributed and local assets (buildings, local energy communities ...) to bring enhanced flexibility and stability at the system level. The benefits of well-controlled transfers between energy vectors will also be investigated

Our strategy focus on the distribution system-scale, studying how the local entities are controlled and interact within this scale. A key issue will be to enable up-scaling of these local entities without jeopardizing the whole system. The interactions between this distribution scale and the transport scale could be integrated in the studies when necessary.

These topics are already widely addressed by the research community. Therefore, we propose a Call for Proposals to detect and fund the best proposals submitted by research groups consortium (see section 5.3.2.212.4.1 for the call description).

### 4.3.3 Ant.3 - Resilience of electrical grids with massive renewables

#### 4.3.3.1 Background and context

The Winter 2021 blackout in Texas has shown the importance of reinforcing the resilience of energy systems. More than 4.5 million customers were left without electricity and the economic cost was huge (around \$130 billion). A cascade of failures resulted of the winter storm Uri and the strong imbalance between production and demand led the operator to cut off customers' electricity. Among the causes of this dramatic event, there were the loss of wind turbine production due to low winds and frozen conditions, malfunctions of power equipment not

<sup>52</sup> C. Rae, S. Kerr, and M. M. Maroto-Valer, "Upscaling smart local energy systems: A review of technical barriers," *Renewable and Sustainable Energy Reviews*, vol. 131, p. 110020, Oct. 2020, doi: 10.1016/j.rser.2020.110020.

<sup>53</sup> F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and Challenges of Low-Inertia Systems (Invited Paper)," in *2018 Power Systems Computation Conference (PSCC)*, Jun. 2018, pp. 1–25. doi: 10.23919/PSCC.2018.8450880.

<sup>54</sup> D. Shelar, S. Amin, and I. Hiskens, "Resilience of Electricity Distribution Networks - Part II: Leveraging Microgrids," *arXiv:1812.01745 [math]*, Dec. 2018, Accessed: Aug. 30, 2019. [Online]. Available: <http://arxiv.org/abs/1812.01745>

<sup>55</sup> Y. Wang, Z. Su, Q. Xu, T. Yang, and N. Zhang, "A Novel Charging Scheme for Electric Vehicles With Smart Communities in Vehicular Networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 9, pp. 8487–8501, Sep. 2019, doi: 10.1109/TVT.2019.2923851.

<sup>56</sup> D. K. Molzahn, F. Dörfler, H. Sandberg, S. H. Low, S. Chakrabarti, R. Baldick, J. Lavaei. A survey of distributed optimization and control algorithms for electric power systems. *IEEE Transactions on Smart Grid* 8 (6), 2941-2962, 2017.

<sup>57</sup> IRENA , "Advanced forecasting of variable renewable power generation: Innovation Landscape Brief," report, 2020.

enough winterized and cut off of the electricity supply of gas producers by operators because the producers sign for low tariffs interruptible power contract<sup>58</sup>.

Natural disasters and extreme weather events were already known to cause large damages to energy infrastructures<sup>59</sup> and this could be even worse with the climate change. Renewable energy sources are sometimes mentioned as an additional mean to prevent from blackout because they enable a more local control of the balance between production and demand<sup>60</sup>. However, they are also more sensitive to weather conditions and they decrease the global inertia of the system and it appears now necessary to adapt the classical frameworks used to study resilience of energy systems<sup>61</sup>. Enhanced frameworks should be able to qualify and quantify the causes and consequences of failure cascades. It should give answers to following questions:

- what are the dynamics of cascades and the transition times?
- how cascades are triggered by weather events?
- what is the impact of a massive share of renewables?
- what roles play the actors of the decentralized and liberalized energy system?
- what is the impact of the climate change?

#### 4.3.3.2 PEPR strategy

Our strategy aims to address this problem in a multidisciplinary manner. We want to gather experts in climate, risks, optimization and power systems to propose a framework able to identify emerging vulnerabilities of energy systems and engineer their resilience. Even if the coupling between electricity and other energy vectors may play a major role as previously seen in Texas, we want to focus on the power system blackouts first, being the main point of connection of renewable energy sources and very sensitive to weather conditions due to the overhead lines. Resilience is a systemic feature and our strategy will not focus on a particular space scale, considering a broad scale from regional to more local scales. Our strategy will focus the following bottlenecks:

- Developing new techniques that provide relevant representation of extreme weather events to derive climate hazards for renewable resources.
- Understanding the events that increase the vulnerability of the electrical grid as well as proposing technical or strategic solutions to prevent major incidents with multidisciplinary and multi-scale temporal and spatial modelling.
- Developing systemic risk analysis methods that integrate weather events, hardware failures and customer behaviors to identify most important dysfunctional interdependencies, and the scenarios to be studied during system downfall or its return to service.
- Solving recovery plans optimization problems that will correspond to robust optimization problems. These problems are known to challenge the most advanced techniques in the field.

<sup>58</sup> J. W. Busby et al., "Cascading risks: Understanding the 2021 winter blackout in Texas," *Energy Research & Social Science*, vol. 77, p. 102106, Jul. 2021, doi: 10.1016/j.erss.2021.102106.

<sup>59</sup> Y. Wang, C., J. Wang, and R. Baldick, "Research on Resilience of Power Systems Under Natural Disasters—A Review," *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1604–1613, Mar. 2016, doi: 10.1109/TPWRS.2015.2429656.

<sup>60</sup> M. Panteli and P. Mancarella, "The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience," *IEEE Power and Energy Magazine*, vol. 13, no. 3, pp. 58–66, May 2015, doi: 10.1109/MPE.2015.2397334.

<sup>61</sup> B.-J. Jesse, H. U. Heinrichs, and W. Kuckshinrichs, "Adapting the theory of resilience to energy systems: a review and outlook," *Energ Sustain Soc*, vol. 9, no. 1, p. 27, Dec. 2019, doi: 10.1186/s13705-019-0210-7.

Our strategy will not include the cybersecurity aspects. They are indeed already addressed in another PEPR program on Cybersecurity and the more specific security issues related to digitalization of energy networks will be studied in the Sys-Tec axis.

This crucial topic will be addressed through a Call for Expression of Interests that will facilitate the emergence and the structuration of a multidisciplinary consortium with the required skills (see section 12.5.2 for the call description).

#### 4.4 Accelerating breakthrough innovation in energy technologies ("Technologies" – Tec.)

The energy transition relies on a whole range of innovative and constantly evolving solutions, in a highly competitive global context. The costs of technologies currently on the market (particularly PV and wind) are being reduced significantly and performance is constantly being improved. Moreover, the integration of renewable energy sources is creating new needs in terms of network management, which is conducive to the emergence of innovation. Technological advance is consequently a fundamental parameter, which implies support for innovation throughout the maturity continuum in order to guarantee sustainable French competitiveness in this sector, allowing the emergence of a solid industrial sector. Beyond the purely competitive aspects, innovation must also make the energy transition accessible to the greatest number of people by developing reliable and affordable solutions.

The PEPR aims to support the French academic excellence and promotes the implementation of the technological component of the PEPR targeting the following two axes:

1. Development of models and tools for flexible and resilient energy networks (Sys-Tec.)
2. Development of photovoltaic cells with high overall potential, high efficiency and minimal environmental impact (PV-Tec.)

##### 4.4.1 Flexible and resilient networks (Sys-Tec)

In its roadmap for 2050, IRENA (International Renewable Energy Agency) proposes a global energy transformation combining greater energy efficiency and the massive use of renewable energy. To keep the temperature rise below 2°C, the development of renewable energies will have to be six times faster<sup>62</sup>. These measures will have a strong impact on energy infrastructures: development of heating networks, large-scale electricity storage, recharging infrastructures, use of flexibilities (control of electric vehicle recharging, smart meters, cross-sector flexibility between diverse energy vectors), and development of smart energy systems to optimize infrastructures' operations and resilience.

Technological advance is a fundamental parameter that implies support for innovation throughout the maturity continuum in order to guarantee and speed-up French competitiveness in this sector. Beyond the purely competitive aspects, innovation must also make the energy transition fully effective by developing reliable and affordable solutions.

Our program proposes to focus on two key enablers for energy transition: DC networks and digitalization of energy systems.

<sup>62</sup> D. Gielen, and al., "The role of renewable energy in the global energy transformation," Energy Strategy Reviews, vol. 24, pp. 38–50, Apr. 2019, doi: 10.1016/j.esr.2019.01.006.



#### 4.4.1.1 Sys-Tec. 1 - DC networks architecture and power electronics

##### 4.4.1.1.1 Background and context

DC networks are proven solutions for connecting DC sources or loads, for interconnecting AC systems. They have been widely used for LVDC microgrids (*Low-Voltage Direct Current*, i.e. <1.5 kV DC)<sup>63</sup>, MVDC (*Medium-Voltage Direct Current*) grids for windfarms, railways or ships and HVDC for supergrids (*High-Voltage Direct Current*, i.e. >100 kV DC)<sup>64,65</sup>. MVDC grids are also proposed for distribution grids to develop interties between renewables, substations, AC grids or large loads<sup>66</sup>. Main challenges of DC networks design are structural design (radial or meshed networks), converters topology, network and converters control, protection<sup>67,68,69</sup>. In 2019, a CIREN working group<sup>70</sup> promote the use of DC networks for the future of power systems. They underline the advantages and functionalities of MVDC link solutions (more active power, no reactive power, improved power quality, control of power flow, *blackstart* capability ...) and the possible use cases<sup>71</sup>.

The deployment of MVDC grids coupled with LVDC microgrids and AC grids is a key issue for the future of power systems with a massive share of renewables and DC loads. In the near future, MVDC grids are expected to be used for power distribution in urban area<sup>72</sup>. However, the MVDC technologies are still project driven and there is no unified view on what would be the best solutions.

##### 4.4.1.1.2 PEPR strategy

In this context, our program aims at proposing a holistic design of structure, control and protection of MVDC grids. The considered use case will be overlay MVAC (Medium Voltage Alternative Current) and MVDC distribution networks. The holistic design intends in identifying the best choices for the grid and the power electronic converters as both are closely coupled. Our strategy will focus on the structural and operational choices for the MVDC networks and what are the constraints imposed by these choices on the converters' design (adapted power structures, control strategies). On the other hand, the performances in normal and grid fault conditions and the services brought by the converters to the grid will be assessed to determine the MVDC design choices. A particular attention will be brought to the converters used for network interconnection, between substations or between two different networks as their role will not only be power exchange but also decoupling between the different grids' characteristics and operation (in order to limit their impact on the MVDC grid during transient operations). Novel methods will be proposed to assess the stability of a mixed AC-DC system with a massive connection of low-inertia renewable sources. And a particular attention will be paid on dedicated protection techniques for DC grids and how the grid-interface converters may contribute to this issue.

<sup>63</sup> Based on IEC TR 63282: LVDC systems

<sup>64</sup> Based on IEC 60633:2019 standard.

<sup>65</sup> M. Saeedifard, M. Graovac, R. F. Dias, and R. Iravani, "DC power systems: Challenges and opportunities," in IEEE PES General Meeting, Jul. 2010, pp. 1–7. doi: 10.1109/PES.2010.5589736.

<sup>66</sup> S. Coffey, V. Timmers, R. Li, G. Wu, and A. Egea-Álvarez, "Review of MVDC Applications, Technologies, and Future Prospects," *Energies*, vol. 14, no. 24, p. 8294, Dec. 2021, doi: 10.3390/en14248294.

<sup>67</sup> J. Saat, R. Bleilevens, D. Mildt, J. Priebe, N. Wehring, and A. Moser, "Design Aspects of Medium and Low Voltage DC Distribution Grids - An Overview," in 2020 5th IEEE Workshop on the Electronic Grid (eGRID), Aachen, Germany, Nov. 2020, pp. 1–6. doi: 10.1109/eGRID48559.2020.9330652.

<sup>68</sup> A. Giannakis and D. Peftitsis, "MVDC Distribution Grids and Potential Applications: Future Trends and Protection Challenges," in 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Sep. 2018, p. P.1-P.9.

<sup>69</sup> J. Priebe, N. Wehring, and A. Moser, "Planning and Design of Medium Voltage DC Grids— An Overview," in 2018 53rd International Universities Power Engineering Conference (UPEC), Glasgow, Sep. 2018, pp. 1–6. doi: 10.1109/UPEC.2018.8541919.

<sup>70</sup> <http://www.cired.net/cired-working-groups>

<sup>71</sup> CIREN, DC Distribution Networks - WG 2019-1, Final report, <http://www.cired.net/cired-working-groups/dc-distribution-networks-wg-2019-1>

<sup>72</sup> CIGRE, Medium voltage direct current (MVDC) grid feasibility study, <https://electra.cigre.org/u/GG-37bc79>

An already well structured research community exists in France. These research units are federated at national level by CNRS in GDR SEEDS. In order to provide an accelerating development of DC architectures and power electronics, this topic will be addressed through a targeted involving the research units in collaborative works (see section 12.3.2 for the project description).

#### 4.4.1.2 *Sys-Tec. 2 - Digitalizing power grids*

##### 4.4.1.2.1 Background and context

Smart energy systems result from the convergence of energy systems, Internet of Things and digitalization. They are key enablers of energy transition. They allow the connection and operation of generators of all sizes and technologies while facilitating the active role of consumers. They provide information to any system's actors. Their goal is to ensure high levels of efficiency, quality, reliability and security.

To achieve their objectives, smart energy systems are cyber-physical power systems gathering production, loads, storage and digital technologies. The latter include metering and monitoring equipment, cloud and/or edge computing infrastructures and network communications<sup>73,74</sup>. They provide computation intelligence and automation to supervise and control smart energy systems. With the massive share of renewables, storage and active loads, the amount of data to be manipulated is becoming larger and larger. Other challenges related to data in smart energy systems are security<sup>75,76</sup>, privacy<sup>77</sup>, interoperability<sup>78,79</sup>. Digital technologies shall be designed in order to provide competitive answers to these issues and enhance the capability of energy systems to host a massive number of very diverse entities.

##### 4.4.1.2.2 PEPR strategy

Our strategy first targets the deployment of distributed intelligence for smart grids operation. Smart grids are indeed a central element for energy transition. The main purpose is to propose advanced middleware architectures and distributed learning techniques for use cases of smart grids, related to either forecast or control.

Our program also focuses on the many technological advances that are required for the digitalization of energy systems, including easy deployment of key enabling technologies such as high performance and/or low cost communication architectures, *blockchains* and distributed ledger technologies, among others. Our strategy finally intend in developing technological bricks for digital twins. The combination of numerical techniques, physical models and data should give an enhanced virtual view of the energy system behavior in real time allowing to enhance its controllability and performances and forecast its evolution.

Two instruments will be used in this sub-axis to fund the research works. A targeted projected involving a small consortium of skilled research groups will address the deployment of distributed intelligence in order to be able to deliver a middleware architecture and distributed techniques at the project term (see section 12.3.3 for the project description). For the other

<sup>73</sup> C. Cecati, G. Mokryani, A. Piccolo, and P. Siano, "An overview on the smart grid concept," in IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society, Nov. 2010, pp. 3322–3327. doi: 10.1109/IECON.2010.5675310.

<sup>74</sup> V. C. Gungor and al., "Smart Grid Technologies: Communication Technologies and Standards," IEEE Trans. Ind. Inf., vol. 7, no. 4, pp. 529–539, Nov. 2011, doi: 10.1109/TII.2011.2166794.

<sup>75</sup> A. Takiddin, M. Ismail, U. Zafar, and E. Serpedin, "Robust Electricity Theft Detection Against Data Poisoning Attacks in Smart Grids," IEEE Transactions on Smart Grid, vol. 12, no. 3, pp. 2675–2684, May 2021, doi: 10.1109/TSG.2020.3047864.

<sup>76</sup> A. Sanjab and W. Saad, "Data Injection Attacks on Smart Grids With Multiple Adversaries: A Game-Theoretic Perspective," IEEE Transactions on Smart Grid, vol. 7, no. 4, pp. 2038–2049, Jul. 2016, doi: 10.1109/TSG.2016.2550218.

<sup>77</sup> F. Skopik, "Security Is Not Enough! On Privacy Challenges in Smart Grids," SGCE, pp. 7–14, 2012, doi: 10.12720/sgce.1.1.7-14.

<sup>78</sup> R. Ma, H.-H. Chen, Y.-R. Huang, and W. Meng, "Smart Grid Communication: Its Challenges and Opportunities," IEEE Transactions on Smart Grid, vol. 4, no. 1, pp. 36–46, Mar. 2013, doi: 10.1109/TSG.2012.2225851.

<sup>79</sup> Z. Fan et al., "Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities," IEEE Commun. Surv. Tutorials, vol. 15, no. 1, pp. 21–38, 2013, doi: 10.1109/SURV.2011.122211.00021.

topics related to an accelerated digitalization of energy systems, a Call for Proposals will be launched to identify the best research proposals (see section 12.4.3 for the call description).

#### 4.4.2 Accelerating innovation for efficient and sustainable photovoltaics (PV-Tec)

The objectives of the French energy policy give a large place to photovoltaics, which should see its installed power multiplied by 4 by 2028. It could then represent more than 10 % of the national electricity production and then continue to grow in the long term. This level of development implies defining a new strategy to take full advantage of the technology's high public acceptability and low cost of electricity production. The cost of photovoltaic electricity should continue to fall in the coming years, in part owing to, the increase in the efficiency of photovoltaic devices, to which the emergence of new concepts and new cell architectures is continually contributing. However, this technology currently has limitations linked to its environmental and territorial footprint, its life cycle, including the low recyclability of some of its components and the dependence on the components of certain critical/strategic materials. Furthermore, most industries producing solar cells are nowadays located out of Europe and France's industrial positioning in the high-efficiency technologies of the future will be conditional on significant prior support for the research programs devoted to them. All these issues are well known and part of several European roadmaps, the latest one being delivered by ETIP-PV<sup>80</sup>.

Three major challenges must be met from a research point of view:

- Development of very high efficiency PV cells with technologies that will prepare for longer-term industrialization phases;
- Acceleration of the development cycle of the new PV technologies
- Improvement of the lifecycle including new high value-added recycling processes for photovoltaic cells and modules, in order to improve the quality and functionality of the recycled materials and thus their outlets. This should also initiate the implementation of a circular economy within the photovoltaic sector or with related industrial sectors, considering also the issue of strategic materials in development.

The development of Life Cycle Assessment (LCA) tools mentioned in Integration axis will usefully support the analysis of the proposed challenges. No specific research action is planned in this program on the recycling of current PV modules, as this is already treated in the PEPR "Recycle".

##### 4.4.2.1 *Innovative and efficient photovoltaic cells with strongly reduced critical element reliance (PV-Tec.1)*

Silicon solar cells represent nowadays 96 % of the current photovoltaic market, with efficiencies up to about 22 % for commercial modules, and 26.7 % for record solar cells, close to the theoretical Shockley-Queisser limit of 29.4 %. About 92 % of the global Photovoltaic (PV) module production (~140 GW<sub>p</sub>) is from Asia in 2020<sup>81</sup>. Re-starting a competitive PV industry in France requires making a breakthrough decrease in the module production cost, the main lever of which is a step gain in the module performances, and/or proposing innovations opening new markets. The use of tandem devices to exploit more efficiently the

<sup>80</sup> <https://etip-pv.eu/> , "Strategic Research and Innovation Agenda on Photovoltaics", Nov 2021

<sup>81</sup> <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>



solar spectrum is expected to increase the efficiency by over 5 % absolute (from ~25 % for the state-of-the-art silicon based device to more than 30 % for a silicon/top cell architecture).

Higher efficiencies are of particular importance for several reasons:

- i. Most PV system costs scale with the area, not only PV module costs but also those of many balance-of-system / components. Thus, increasing the  $W_p/m^2$  or ultimately  $kWh/m^2$  through higher efficiencies has a very strong leverage for reducing LCOE.
- ii. Increasing electrification of our energy system and the growing demand for electricity from sectors like heating and cooling, transport and chemical conversion require high performing electricity generation. In urban Europe, local electricity generation and storage can reduce transmission costs substantially but available area on buildings, infrastructure etc. needs to be used as effectively as possible.
- iii. In a multi-terawatt (TW) PV industry, other resource constraints become challenging, ranging from metal depletion to available production capacities. Again, higher efficiencies can help to alleviate these constraints.

Next-generation solar cells should target efficiencies beyond 30 %, and require the development of new concepts. Tandem solar cells are considered as the most promising technology, but performances >30 % have been obtained with costly III-V multi-junctions and III-V//Si tandem solar cells. Other materials are also intensively investigated in the PV community (perovskite, CIGS, organic), but they all require further improvements (efficiency and stability in particular) and new technological developments to become industrially viable.

#### 4.4.2.1.1 Background and context

The main solar cell technology is based on crystalline silicon with nearly 96% of the market, the remaining 4 % being occupied by CdTe [Cadmium-Tellurium], CIGS [based on  $CuInGa(Se)_2$ ] and amorphous silicon thin film technologies covering respectively 2.3 GW<sub>p</sub>, 1.9 GW<sub>p</sub> and 0.3 GW<sub>p</sub> in 2017. Crystalline silicon technology is far from being monolithic, with several architectures (PERL, PERC, HIT, IBC...) with the highest efficiencies currently being obtained with the HIT-IBC technology with performances above 26 %<sup>82</sup>. This technology is very mature and close to limiting efficiencies, so that most efforts are in optimizing manufacturing to reduce cost and material issues (Kerf loss, use of Ag ...) <sup>82,83</sup>. At the same time, for thin films, technological progress in the CdTe (22.1 % record efficiency) and CIGS<sup>84</sup> (23.3 %) <sup>82</sup> technologies is very significant and concerns the architectures and materials used. Note the development of CIGS technologies on flexible and light supports, which reach record yields (20.8 %) <sup>82</sup> in the laboratory and on a commercial level (18 %) <sup>85</sup>. Other technologies exist at the commercial level but in much smaller markets. These are the very high efficiency GaAs family of cells, known as three-five "III-V" cells, which operate in the form of multi-junctions and which are used for space and terrestrial applications under concentration. Note that the all-time record efficiency of 47.1 % is achieved with this family of technologies with 6-junction cells operating under a concentration of 173 suns. Yet another emerging technology, organic photovoltaic (OPV) technologies start entering the market, still on niche applications, but whose development potential is significant due to low manufacturing costs and ability to address application that require flexible and lightweight modules. The recent progress in the efficiencies of these materials in the laboratory (20 % for tandem cells<sup>86</sup>, and 14 % for a mini-module<sup>82</sup>) gives these technologies a significant margin of progress despite the difficulties still

<sup>82</sup> Solar cell efficiency tables (version 59); DOI: 10.1002/pip.3506

<sup>83</sup> <https://pv-manufacturing.org/wp-content/uploads/2019/03/ITRPV-2019.pdf>

<sup>84</sup> <https://cigs-pv.net/cigs-white-paper-2019-now-available/>

<sup>85</sup> <https://miasole.com/>, USA

<sup>86</sup> <https://doi.org/10.1016/j.joule.2021.12.017>

present, particularly in terms of aging. Finally, great efforts are being made to move towards the commercialization of hybrid perovskite technology, whose efficiencies are impressive (25.7%) but which still suffers from stability issues of and extension to large surfaces. All the emerging current thin film technologies suffer from severe stability issues, so that in spite of their attractiveness, no sure bet on their industrialization can be made. All of the current thin film technologies are rather well developed in terms of deposition processes but suffer from a lack of technology on light trapping, passivation, contacting, etc, so that their full potential is not yet unlocked, contrary to c-Si technology.

#### 4.4.2.1.2 PEPR strategy

The goal of this project is to develop new routes for low-cost, high-efficiency tandem solar cells. It will focus on thin-film/silicon solar cells in order to take advantage of the industrially mature silicon technology for the bottom cell, and it will keep several options for the top cell. This is preparing future evolution on the longer term of the technologies: when Thin Film on Si Tandem is ready at the manufacturing level, it will be a major step towards full Thin Film tandem, which will reduce the cost and environmental footprint of the technology while unlocking new applications and markets.

Key technological building blocks will be developed (photon management, material deposition, interfaces, and breakthrough technologies) to enable novel architectures compatible with the efficient materials already available, keeping an openness on materials and architectures, and favoring transverse actions. Novel architectures will be developed to accelerate the integration of thin-film on silicon solar cells at low cost, having in mind the reduction of usage of critical material and ability to transfer the breakthrough technologies developed at low TRL to processes that could be used realistically in industry. Breakthrough efficient (>30%) functional devices are expected at the end of the project.

The community working on these aspects is well identified and already working together in several networks (FedPV, Nanorgasol) and around ITE (INES2S, IPVF). The targeted project is organized around the development of technological bricks and their integration: management of photons in the tandems, interlayers, development of processes with low thermal budget and economical in materials, breakthrough technologies (patterning, hybrid materials, bonding, etc.), and integration with different architectures of tandems (monolithic, bonded, and 3-Terminal devices for improved yield). This is addressed through actions of process development, modelling and characterization (see section 12.3.4 for the project description).

A specific project, to be defined through an AAP, will be aiming at the substitution of critical materials in the transparent contacting layers (TCL) and in the metallic grid. It will be carried out through an AAP, to identify best solutions, including some that may not have been identified during the writing of the PEPR (see section 12.4.4 for the call description).

#### 4.4.2.2 *Ecofriendly and innovative photovoltaic modules (PV-Tec.2)*

##### 4.4.2.2.1 Background and context

Several technologies exist today and their diversification should increase in the future. On the other hand, results show that this diversity and innovation could offer a large potential to reduce environmental impacts. It is therefore necessary to ensure that new PV technologies, which are complex and involve several manufacturing steps, meet the criteria of a low environmental

impact and frugality of the materials integrated into the PV module, so-called eco-designed<sup>87,88,89,90,91</sup>.

The main objective is to integrate therefore in a systemic and perennial way the environmental analysis into the specifications of the project to guide technological choices before further development of the technology. A systemic and perennial approach is therefore needed from the fundamental to low TRL R&D level to foster innovation in building blocks and their integration into an advanced PV module.

#### 4.4.2.2.2 PEPR strategy

In coherence with the work that will be carried out in the targeted project on tandem cells, this targeted project will focus on carrying out the upstream research necessary to give the final envelope the necessary characteristics in terms of performance, durability and competitive industrial potential; in an eco-innovation approach.

The research work carried out in collaboration with the scientific community will focus on three areas:

- Innovative encapsulation technology to facilitate dismantling and recycling, keeping Performance and reliability
- Innovative interconnection cells technologies reducing the use of critical materials
- Solar solutions of built-up areas and societal acceptance: Optical transparency and integration / light-flexible substrate and material reduction

The community working on some of these aspects is well identified and already working together in several networks (FedPV, Nanorgasol) and around ITE (INES2S, IPVF). A targeted project is therefore proposed on three specific aspects: solutions for encapsulation that lead to reversible opening after sealing (Vitrimers, glass-fritt ...) or /and enable lightweight encapsulation, modules for building- or agro- integration, and printed connectors (interconnects, bypass or protection diodes) (see section 12.3.5 for the project description).

A first specific project, to be defined through a CEI, will be aiming at proposing sustainable envelope with reduced environmental impact, where the materials could be biosourced or coming from recycling process. It will be carried out through a CEI, to help structure a project between actors that are not to day working together and where several approaches are possible (see section 12.5.3 for the call description).

A second specific project, to be defined through a CEI and launched later in the course of the program, will be aiming at proposing solutions towards a smart module. This includes integrated sensors and reconfigurable connections and some embarked intelligence. It will be carried out through a CEI, to help structure a project between actors that are not to day working together and where several approaches are possible (see section 12.5.4 for the call description).

<sup>87</sup> SolarPower Europe. « Global Market Outlook for Solar Power 2020-2024 », 2020.

<sup>88</sup> [https://iea-pvps.org/wp-content/uploads/2020/01/IRENA\\_IEAPVPS\\_End-of-Life\\_Solar\\_PV\\_Panels\\_2016.pdf](https://iea-pvps.org/wp-content/uploads/2020/01/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf)

<sup>89</sup> <https://www.sciencedirect.com/science/article/pii/S0959652618319358> : A path to reduce variability of the environmental footprint results of photovoltaic systems \_ N.Gazbour et Al.

<sup>90</sup> <https://www.sciencedirect.com/science/article/pii/S136403211500146X> : Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis

<sup>91</sup> G. A. Heath et al., « Research and development priorities for silicon photovoltaic module recycling to support a circular economy », *Nature Energy*, vol. 5, no 7, p. 502-510, July 2020, doi: 10.1038/s41560-020-0645-2

#### 4.4.2.3 Reliability of innovative devices for accelerated innovation cycles (PV-Tec.3)

##### 4.4.2.3.1 Background and context

While strong effort is being dedicated to increase the efficiency of solar cells, one major issue for the development and expansion of PV is the reliability.

Especially, before new bricks and new technologies can enter in the production of solar modules, it is mandatory to be able to assess quantitatively their reliability, and how they will degrade with time under long-term working conditions.

Standard reliability tests and protocols exist and are commonly used for mature technologies; however, they need to be revisited or may not be relevant for new technologies. In addition, outdoor measurements are important but they need to be done over long periods, and need to be associated with modelling strategies.

Various advanced *in situ/operando* characterization tools have emerged in the past decade, which have facilitated the understanding of the degradation mechanisms and the further development of high-performance batteries<sup>92,93,94</sup>. The use of *in situ/operando* characterization tools<sup>95,96</sup> has also been proposed recently in the field of photovoltaics, since they appear mandatory to analyze changes occurring during operation at the material and interface levels. Some recent work can be found especially for the study of the degradation of perovskite materials<sup>97,98,99,100</sup>. However, the study of reliability and degradation of solar cells cannot be limited to such *in situ/operando* tools<sup>101</sup>, and it also requires complementary *ex situ* multiscale characterization, from various advanced techniques<sup>102,103</sup>.

##### 4.4.2.3.2 PEPR strategy

It is thus important to develop new methodologies and analyses that can tackle the degradation issues at the material, interface, and device levels using accelerated aging procedures. Of particular interest are the *in situ/operando* characterizations where one can observe the appearance of degradation and track their evolution. They will be complemented by selected and combined *ex-situ* characterization tools, as well as by numerical modelling, aiming at providing predictive assessment of the degradation.

<sup>92</sup> P. Noval et al., "Advanced in situ methods for the characterization of practical electrodes in lithium-ion batteries", *Journal of Power Sources* 90 (2000) 52, [https://doi.org/10.1016/S0378-7753\(00\)00447-X](https://doi.org/10.1016/S0378-7753(00)00447-X)

<sup>93</sup> A. M. Tripathi et al., "In situ analytical techniques for battery interface analysis", *Chem. Soc. Rev.* 47 (2018) 736, <https://doi.org/10.1039/C7CS00180K>

<sup>94</sup> D. Liu et al., "Review of Recent Development of In Situ/Operando Characterization Techniques for Lithium Battery Research", *Advanced Materials* 31 (2019) 1806620, <https://doi.org/10.1002/adma.201806620>

<sup>95</sup> J. Tan et al., "In situ/operando characterization techniques for rechargeable lithium–sulfur batteries: a review", *Nanoscale* 9 (2017) 19001, <https://doi.org/10.1039/C7NR06819K>

<sup>96</sup> S-M. Bak et al., "In situ/operando synchrotron-based X-ray techniques for lithium-ion battery research", *NPG Asia Materials* 10 (2018) 563, <https://doi.org/10.1038/s41427-018-0056-z>

<sup>97</sup> U.B. Cappel et al., "Partially Reversible Photoinduced Chemical Changes in a Mixed-Ion Perovskite Material for Solar Cells", *ACS Appl. Mater. Interfaces* 40 (2017) 34970, <https://doi.org/10.1021/acsami.7b10643>

<sup>98</sup> F.U. Kosasih et al., "Characterising degradation of perovskite solar cells through in-situ and operando electron microscopy", *Nano Energy* 47 (2018) 243, <https://doi.org/10.1016/j.nanoen.2018.02.055>

<sup>99</sup> C. Xiao et al., "Operando Microscopy Characterization of Perovskite Solar Cells", *NREL/CP-5K00-73109* (2019), <https://www.nrel.gov/docs/fy19osti/73109.pdf>

<sup>100</sup> W. Yu et al., "Atomic force microscopy: Emerging illuminated and operando techniques for solar fuel research", *J. Chem. Phys.* 153 (2020) 020902, <https://doi.org/10.1063/5.0009858>

<sup>101</sup> Mohammad Ali Akhavan Kazemi et al., "Molecular-Level Insight into Correlation between Surface Defects and Stability of Methylammonium Lead Halide Perovskite Under Controlled Humidity", *Small* 5 (2021) 2000834, <https://doi.org/10.1002/smt.202000834>

<sup>102</sup> *Advanced Characterization Techniques for Thin Film Solar Cells*, edited by Daniel Abou-Ras, Thomas Kirchartz, and Uwe Rau, WILEY-VCH Verlag GmbH & Co. KGaA (2011)

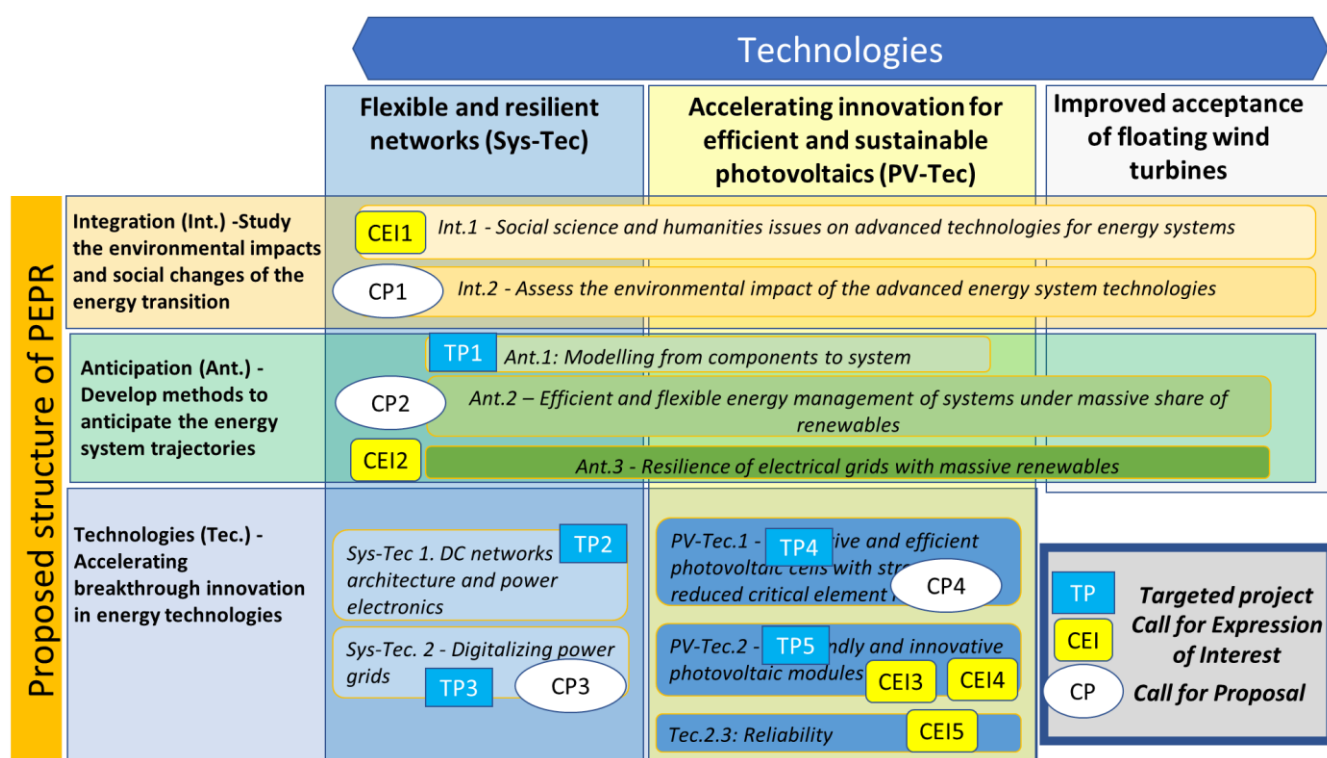
<sup>103</sup> A.Zohar et al., "In Operando, Photovoltaic, and Microscopic Evaluation of Recombination Centers in Halide Perovskite-Based Solar Cells", *ACS Appl. Mater. Interfaces* (2021), <https://doi.org/10.1021/acsami.1c08675>

The community working on some of these aspects is well identified and already working together in several networks (FedPV, Nanorgasol) and around ITE (INES2S, IPVF). Yet there are also other research communities that could potentially bring new ideas and competences, as around large instruments (Synchrotrons Soleil, ESRF...) or in other fields of material science. A specific project, to be defined through a CEI will aim at developing operando techniques, coordinating ex-situ analysis and integrating the knowledge in simulation tools (see section 12.5.3/12.5.5 for the call description).

## 5 IMPLEMENTATION PLAN

### 5.1 Work program structure

The work program structure is shown in the *Figure 14*.



*Figure 14 : Work program structure. TP = Targeted Projects. CP = Calls for Proposals. CEI = Calls for Expressions of Interest.*

As previously mentioned in section 4.1, there is no specific technological development on wind turbines as stated by the National Strategy. But wind production is obviously considered in the Anticipation axis, especially for advanced methods of management and resilience studies.

### 5.2 Process for building the proposed programme

The process of on-going completion towards a final document is described in *Figure 15*. The PEPR pilots presented the progress of the construction on a regular review with the coordination of the National Strategy. Several entities were also contacted and consulted (see below).



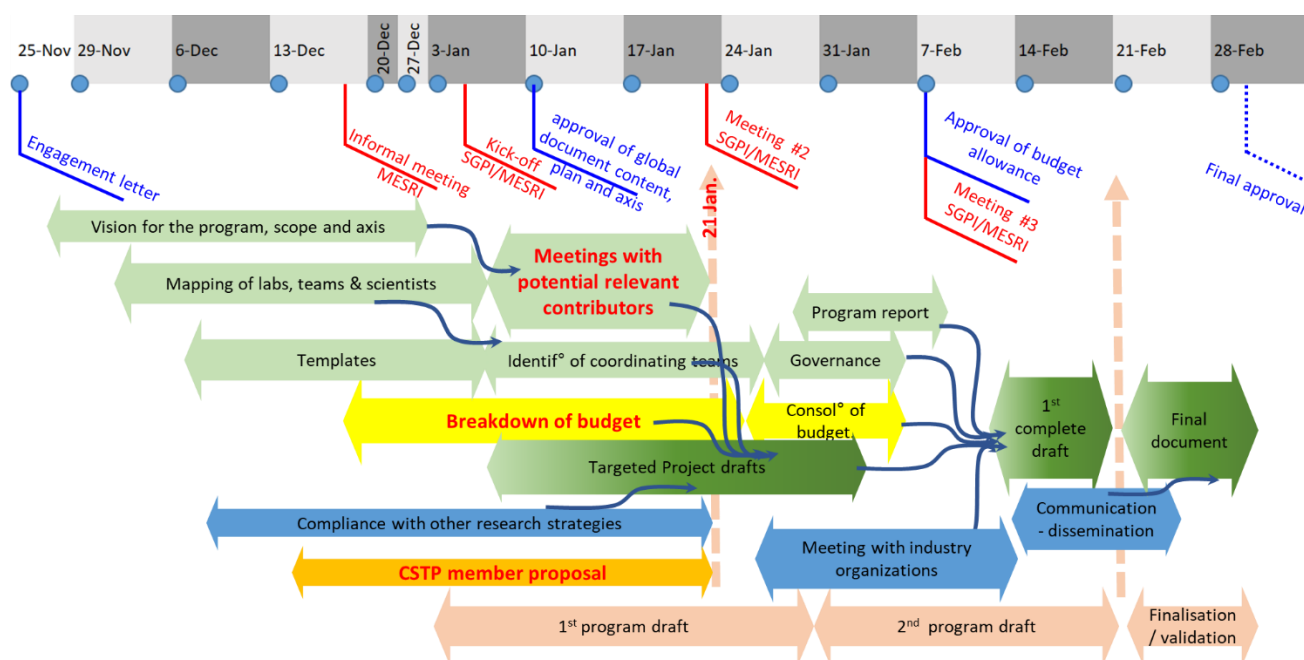


Figure 15 : process for building the proposed programme

## 5.2.1 Transparency and consultation of the scientific community

### 5.2.1.1 Assessment and launch of the consultation

The PEPR TASE addresses rather large and diversified communities. We made a wide consultation of all potential research actors. We collected responses giving an overview of nearly 140 laboratories / research entities in France. From these responses, we were able to obtain 20 to 80 contacts for each theme, with multiples answers in some cases, as shown in the following table:

Themes	Int	Ant	Sys-Tec	PV-Tec
Answers	32	21	54	83

### 5.2.1.2 Identification of coordinating teams

We proposed a coordinating team for each sub-axis, always from two different entities and preferably targeting good complementarity.

Each coordinating team was handled the lists of contacts that had been collected in order to form a thematic panel that would identify the scientific and technical obstacles to be addressed as a priority in their field, in line with the issues mentioned in the mission statement and the vision of pilots. This vision was previously share with the SGPI at the kick off meeting.

The thematic panels and their geographic origin are presented in Figure 16. For the sake of balance within the scientific community and to allow for efficient discussions, the number of entities involved in the panels was deliberately kept small. For the CP and CEI, the draft texts of the calls were circulated more widely within the communities initially identified by the consultation.

For the targeted projects, the coordinating team constituted its consortium with the help of the program pilots and the consultation answers.



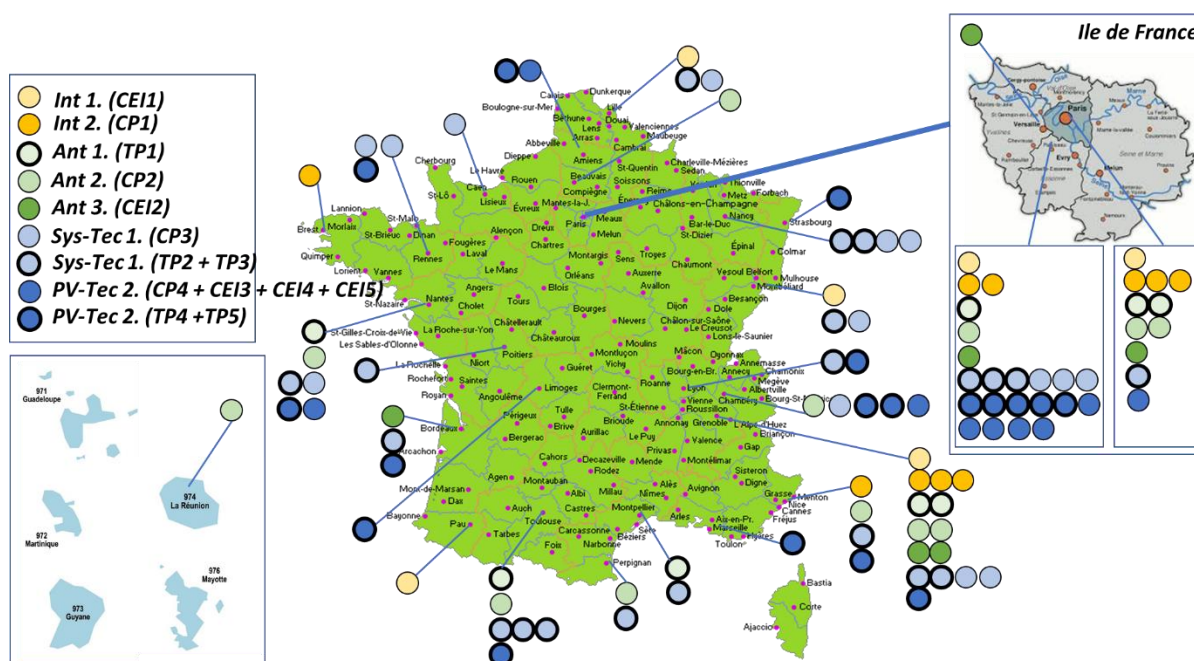


Figure 16 : Breakdown of participation in targeted projects (TP - circles circled in **bold**), drafting of Calls for Proposals (CP) and Calls for Expressions of Interest CEI).

### 5.2.2 Breakdown of the budget

The budget breakdown by axis is shown in the Figure 17.

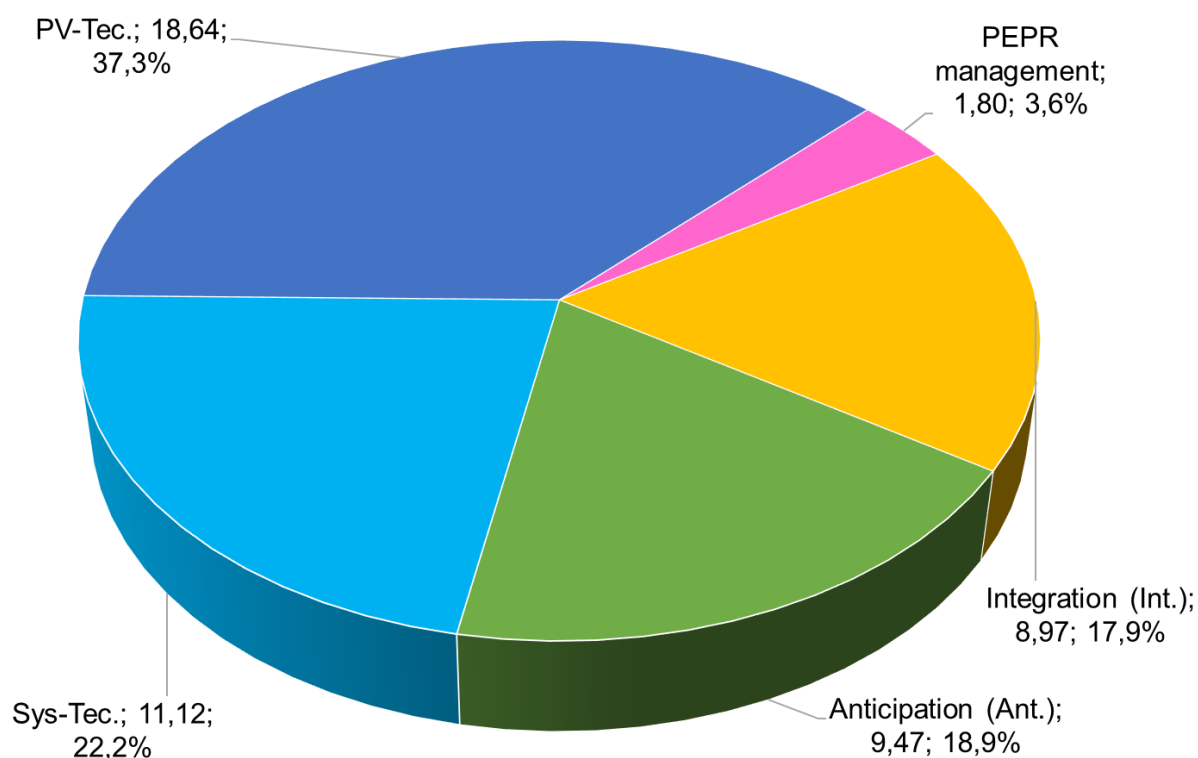


Figure 17 : budget breakdown by axis. Numbers are given in M€ and percentage figures refer to the total budget (50 M€).

Taking into account the balances mentioned above and the choices made based on the feedback from the pairs, the final budget allocation is as follows (*Figure 18*):

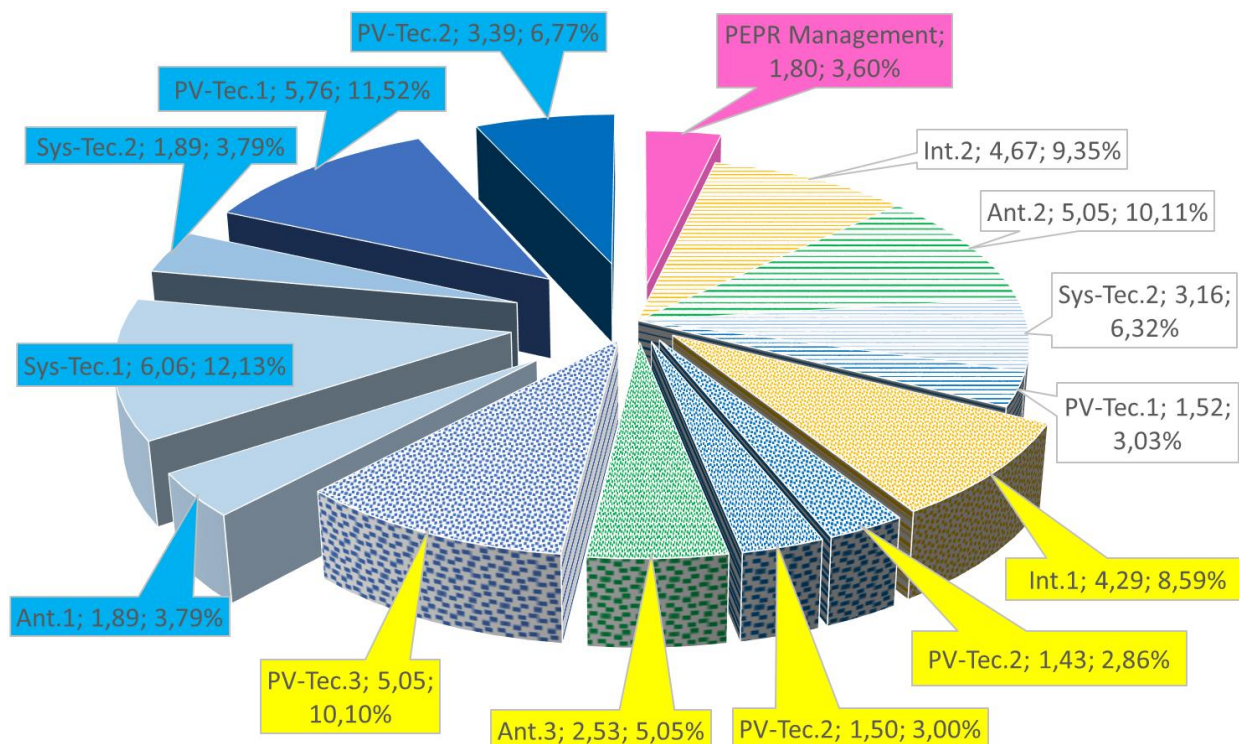


Figure 18 : distribution of actions and budgets. Colors of speech balloons refer to the type of action. Pink: PEPR management. In white: Call for Proposals (CP). In yellow: Call for Expression of Interest (CEI). In blue: targeted projects (TP). Numbers are in M€ and percentage figures refer to the total budget (50 M€).

Table 1 : summary of budget allocations according to PEPR actions.

Action	budget allocation (%)
PEPR management	3,60%
Call for Proposals (CP)	28,80%
Call for Expression of Interest (CEI)	29,60%
Targeted Projects (TP)	38,00%

### 5.3 Details of the programme

#### 5.3.1 The Targeted Projects (TP)

##### 5.3.1.1 TP coordinators

Target project name	Coordinator	Affiliation
TP 1 - HyMES	Bruno Lacarrière	Institut Mines Telecom
TP 2 - DC-ARCHITECT	Vincent Debusschère	Univ. Grenoble Alpes
TP 3 - AI-NRGY	Cédric Auliac	CEA
TP 4 - IOTA	Stéphane Collin	CNRS
TP 5 - Smart4Modules	Aude Derrier	CEA

### 5.3.1.2 TP 1 - HyMES - Hybrid modelling for Multi Energy Systems

The project aims at developing new modelling methods and strategies compatible with the complexity of Multi Energy Systems (MES) in the case of electricity and thermal energy networks coupling. In particular, the work will study the relevance of hybrid modelling solutions and the appropriate ways on their implementation. Hybrid Modelling (HM) is understood here as the combination of Physics Based Modelling (PBM) and Machine Learning (ML) solutions, in order to take the best advantage of data profusion available for these systems at the city scale, while keeping models' results explainable.

#### Milestones

M1 (T0+12M): Characterization of usual modelling limitations for MES

M2 (T0+36M): Classification of relevant hybrid approaches for MES

M3 (T0+48M): Degree of hybridization for change in scale

M4 (T0+24M): Initial version of benchmark

M5 (T0+60M): Open version of benchmark available to research community

In addition, 4 workshops will be organized during the project duration, one over year, except the last one.

**Required resources** – 1.9M€ (full cost, incl. 6 PhDs and 2 PostDocs)

#### Partners

Partner number	Laboratory name (Acronym) <sup>104</sup>	Name of the organism <sup>105</sup>	Localization (city)
P1	GEPEA	UMR 6144 GEPEA - CNRS/IMT Atlantique	Nantes
P2	CEA/DRT/LITEN and CEA/DES/ISAS	CEA	Grenoble and Saclay
P3	Laplace	UMR CNRS 5213 INP-ENSEEIH	Toulouse
P4	ISIR	UMR 7222 - CNRS/ Sorbonne Université	Paris
P5	IES	Université de Montpellier - CNRS - UMR 5214	Montpellier
P6	G2ELab	UMR 5269 Université de Grenoble - (CNRS - Grenoble-INP - UGA)	Grenoble
P7	CEDRIC	EA 4629 - CNAM Paris	Paris
P8	PROMES	CNRS UPR-8521 - Université de Perpignan Via Domitia	Perpignan

<sup>104</sup> For CNRS labs, indicate the identification number, e.g. UPM/UPR xxxx

<sup>105</sup> CNRS, IFPEN, CEA, Université de ..., for UMR indicate all the supervisory authorities

### 5.3.1.3 TP 2 – DC-ARCHITECT - Co-designing the future of MV distribution grids with their power electronics components

This project aims at developing a holistic design of structure, control and protection of MVDC (Medium Voltage Direct Current) grids. The considered use case will be overlay MVAC (Medium Voltage Alternative Current) and MVDC distribution networks. The holistic design intends in co-identifying the best choices for the grid and the Power Electronic Converters (PEC) as both are closely coupled. The converters will be designed to provide advanced ancillary services to the grid, as well as aging monitoring for improved durability.

#### Milestones

- Project coordination and preparation done - Successful end of project
  - Ms1 (T0+3): Project Coordination scheme
  - Ms2 (T0+60): End of project report
- Design principles of the architecture of the grids and their operation, specifications for PEC
  - Ms3 (T0+18M): Initial results on study cases of hybrid AC DC hybrid architectures and initial PEC specifications. Pre-normalization proposal for grid operation
  - Ms4 (T0+36M): End of WP1 report
- PEC architectures and diagnostic methods
  - Ms5 (T0+30M): Initial results on four PEC architectures and their local control. Ageing assessment and state of health of components
  - Ms6 (T0+48M): End of WP2 report
- System validation for defined use case
  - Ms7 (T0+42M): Initial results on methods for stability study and protection of hybrid distribution grid.
  - Ms8 (T0+60M): End of WP3 report

**Required resources** – 6.2M€ (full cost, incl. 16 PhDs)

#### Partners

Partner number	Laboratory name (Acronym)	Name of the organism	Localization (city)
P1	G2ELAB / UMR 5269	CNRS / Grenoble INP / Univ. Grenoble Alpes	Grenoble
P2	CEA-DTS-SIRE-LIRE	CEA	Chambéry
P3	AMPERE / UMR 5005	CNRS/Lyon 1/ EC-Lyon/ INSA-Lyon	Lyon
P4	FEMTO-ST	CNRS / UBFC	Belfort
P5	GEEPS / UMR 8507	CNRS / Univ. Paris-Saclay / CentraleSupélec / Sorbonne Univ.	Paris Saclay / Paris
P6	GREEN	Université de Lorraine	Nancy
P7	IES / UMR 5214	CNRS / Université de Montpellier	Montpellier
P8	IMS	CNRS / Bordeaux INP / Université de Bordeaux	Bordeaux
P9	IREENA	Nantes Université	Nantes

P10	LAAS / UPR 8001	CNRS	Toulouse
P11	LAPLACE	CNRS/Toulouse INP/UT3	Toulouse
P12	LEMTA	CNRS/Université de Lorraine	Nancy
P13	LIAS / EA 6315	ENSI Poitiers	Poitiers
P14	L2EP / ULR 2697	Centrale Lille Institut	Lille
P15	PROMES / UPR 8521	CNRS	Perpignan
P16	SATIE / UMR 8029	CNRS	Paris/Rennes

#### 5.3.1.4 TP 3 - AI-NRGY - Distributed AI-based architecture of future energy systems integrating very large amounts of distributed sources.

This project aims to propose a software architecture as well as the methods, models and algorithms required to implement distributed intelligence solutions likely to accelerate the digitization of energy networks.

##### Milestones

M1 (T0+12M): milestone focused on use cases results and usage

M2 (T0+24M): milestone focused on first use of middleware and first result on the different distributed AI propositions

M3 (T0+36M): milestone focused on advanced use of distributed AI in the simulated Energy architecture

M4 (T0+48M): milestone focused on final workshop to demonstrate and share results of the project

**Required resources** 1.9M€ (full cost, incl. 7 PhDs and 2 Post Docs)

##### Partners

Partner number	Laboratory name (Acronym)	Name of the organism	Localization (city)
P1	IRIT - UMR5505	Institut de Recherche en Informatique de Toulouse	Toulouse
P2	CEA-LIST-DM2I	CEA	Saclay
P3	Centre Inria Paris	INRIA	Paris
P4	PERSEE	ARMINES - MINES Paris	Sophia Antipolis

#### 5.3.1.5 TP 4 - IOTA (InnOvative Tandem Architectures)

This projects aims at providing enabling eco-friendly and sustainable technologies for the next generation of tandem solar cells and to propose disruptive solutions for tandem solar cells in order to reach a target in power conversion efficiency > 30%. To achieve this ultra-ambitious goal, work is divided in transversal technology bricks that can be compatible with different cell architecture and approaches.

- Project coordination
  - Ms1: Project Coordination scheme and consortium agreement
  - Ms2: End of project report
- WP1: Interlayers
  - Ms3: Initial selection of interlayer compounds (T0+30)



- Ms4: End of WP1 report
- WP2: Processes for Perovskite materials
  - Ms5: Initial results on conformal deposition (T0+30)
  - Ms6: End of WP2 report
- WP3 : Breakthrough nanotechnologies
  - Ms7: Initial results on nanopatterning (T0+24).
  - Ms8: End of WP3 report
- WP4: Integration
  - Ms9: Initial results on 2T and 3T tandems
  - Ms10: End of WP4 report

Composition of the consortium			
Partner number	Laboratory name (Acronym) <sup>106</sup>	Name of the organism <sup>107</sup>	Localisation (city)
P1	C2N	CNRS	Palaiseau
P2	CEA-LITEN-DTS	CEA	Grenoble
P3	IPVF	CNRS	Palaiseau
P4	IMN	U. Nantes	Nantes
P5	INL	CNRS	Lyon
P6	LAAS	CNRS	Toulouse
P7	LPICM	CNRS	Palaiseau
P8	GeePs	CentraleSupélec	Gif
Collaborations	SYMMES, CRHEA, FOTON, ILV, LMGP, FEMTO-ST, iCube, IMS		

#### 5.3.1.6 TP 5 - Smart4Module - Smarter and Eco Innovation building blocks for advanced PV Module

- i- This targeted project aims at seeding innovative and more eco-responsible building blocks to prepare the next generation of PV modules and tandem devices having: longer-term durability and improved sustainability thanks to new types of encapsulation,
- ii- a higher level of conceptualization of thin film processing including not only the printing of active materials but also the connectors, interconnections and bypass diodes to prepare lower environmental impact and smarter modules,
- iii- exploring novel possibilities of PV module integration in our environment having adaptable level of coloration, semi-transparency to even fully non-intrusive aesthetics for improved social acceptance.

The tryptic between LCA indicators, performance/reliability with respect to the state-of-the art and potentialities for technological transfer will be also assessed.

- Project coordination
  - Ms1: Project Coordination scheme and consortium agreement
  - Ms2: End of project report
- WP1: Sustainable encapsulation
  - Ms3 (t0+24): Initial results on selected encapsulates
  - Ms4: End of WP1 report (t0+60M)

<sup>106</sup> For CNRS labs, indicate the identification number, e.g. UPM/UPR xxxx

<sup>107</sup> CNRS, IFPEN, CEA, Université de ..., for UMR indicate all the supervisory authorities



- WP2: Tunable coloration/transparency
  - Ms5: Initial results (T0+30M)
  - Ms6: End of WP2 report
- WP3 : Integrated circuits
  - Ms7: Initial results (T0+24M).
  - Ms8: End of WP3 report

<b>Composition of the consortium (blue are task leader in the project)</b>			
Partner number	Laboratory name (acronym)	Name of the organism	Localization city
P1	CEA-LITEN-DTS-SMSP	CEA	Grenoble
P2	LAAS	CNRS	Toulouse
P3	IMS	CNRS/UB/Bordeaux INP	Bordeaux
P4	LRCS	CNRS/Université de Picardie Jules Verne	Amiens
P5	PIMM	CNRS/HESAM Université	Paris
P6	CEMEF	Mines Paris / PSL	Paris
P7	LCPO	CNRS/UB/Bordeaux INP	Bordeaux
P8	LPICM	CNRS/Ecole Polytechnique	Saclay
P9	LCMCP	CNRS / Sorbonne Université	Paris
P10	ESPCI	ESPCI / PSL	Paris
P11	IPVF	CNRS	Palaiseau
P12	LMGP	CNRS/Université Grenoble Alpes	Grenoble
P13	INL	CNRS/Université de Lyon	Lyon
P14	XLIM	CNRS/Université de Limoges	Limoges
P15	IM2NP	CNRS/Université Aix- Marseille	Marseille
P16	LAPLACE	CNRS/Université de Toulouse	Toulouse
P17	CINAM	CNRS/Université Aix- Marseille	Marseille
P18	CEISAM	CNRS/Université de Nantes	Nantes

### 5.3.1.7 Summary of Targeted Projects

Targeted Projects	Challenges	Expected impacts
<p>TP1</p> <p>HyMES - Hybrid modelling for Multi Energy Systems</p>	<p>1- Hybrid model of multi energy systems with an innovative combination of physic-based models and learning models.</p> <p>2- New AI techniques for hybrid modelling of energy systems, incl. emerging PV technologies</p> <p>3- Definition of a benchmark for the test and evaluation of multi energy systems design and operation</p>	<ul style="list-style-type: none"> <li>• Ability to simulate district-scale multi energy systems at a low computing cost</li> <li>• Ability to assess the impact of emerging PV technologies on the multi energy system</li> <li>• Ability to optimize a multi energy system operation</li> </ul>
<p>TP2</p> <p>ARCHITECT - Co-designing the future of MV distribution grids with their power electronics components</p>	<p>1- Innovative holistic design method of Medium Voltage Direct Current (MVDC) distribution grids</p> <p>2- Grid architectures and codes, operational constraints, protection schemes required for resilient, flexible, reliable and efficient MVDC solutions</p> <p>3- Structures and advanced functions of power converters required to support the grid operation.</p>	<ul style="list-style-type: none"> <li>• Ability of proposed specifications and related architectures for MVDC solutions to integrate effectively a massive share of renewables</li> <li>• Ability of power electronics converters to efficiently support the grid operation in normal and faulty conditions</li> <li>• Qualification of design and system solutions through validating, demonstrating, and evaluating MVDC solutions via case studies and lab tests (ex: Hardware-In-the-Loop –HIL- simulation).</li> </ul>
<p>TP3</p> <p>AI-NRGY - Distributed AI-based architecture of future energy systems integrating very large amounts of distributed sources.</p>	<p>1- Adaptive distributed software architecture in terms of localization of services and data feedback to satisfy performance, privacy or characteristics of support equipment, in particular to distributed AI algorithms</p> <p>2- Distributed AI able to integrate the distribution of data, their possible volatility or the dynamics of access to information</p> <p>3- AI-based solutions with enhanced interpretability/explicability to promote acceptability by end-users</p> <p>4- Extraction of value out of the wealth of data owned by different actors</p>	<ul style="list-style-type: none"> <li>• Ability of the deployed middleware on physical devices and simulated equipment to support edge forecasting</li> <li>• Ability of the distributed intelligent solutions for collaborative forecasting, optimization, real-time control</li> <li>• Open source software developed for data and service deployment</li> </ul>

TP4 Innovative Tandem Architectures (IOTA)	<p>1- Efficiency above 30% for the next generation of photovoltaic device.</p> <p>2- Reduced reliance on critical materials.</p> <p>3- Breakthrough innovation that would encourage investment from private sector to develop a local industry.</p>	<ul style="list-style-type: none"> <li>• Tandem on Si are the next generation of devices with efficiency above 30%.</li> <li>• New architecture will be developed that require less or no critical materials. New architectures will enable IP creation and will foster private investment</li> </ul>
TP5 (Smart4Modules)	<p>1- PV modules should reduce its material content to lower environmental footprint.</p> <p>2- Social acceptance and appropriation of new PV technologies.</p> <p>3- Breakthrough innovation that would encourage investment from private sector to develop a local industry.</p> <p>4- Module based pathways for higher efficiencies and longer term utilization.</p>	<ul style="list-style-type: none"> <li>• New envelopes with low environmental footprint and better reuse of components.</li> <li>• Module as integrated circuit: printing of protection/bypass diodes and busbars. This prefigures the path to smart modules (proposed as CEI).</li> <li>• Photovoltaic functionalization of built surfaces that better integrates with the environment (tunable color, flexibility).</li> </ul>

### 5.3.2 Calls for Proposals

#### 5.3.2.1 CP 1 - *Environmental integration*

Two types of projects are welcome: projects addressing life cycle analysis and environmental impacts on the one hand and projects addressing new usage and applications for improved environmental impacts on the other hand.

The following challenges that are relevant for one of the project types should be addressed:

- Developing dedicated database for environmental impact assessment, including documented metadata: the call will support project developing well-documented, high quality and regional data are needed. In the perspective to expand environmental and socio-economic impacts in the frame of LCSA, the projects should envisage adding economic and social inventories and indicators to the environmental framework. In addition, assessment experts may have difficulties in judging the data selection if they are not experts in all subjects of the study. Therefore, interdisciplinary collaboration between assessment experts and researchers from other expertise domains is sought.
- Assessing LCA uncertainty: the call will support projects that identify uncertainty sources in the LCA process, determine how uncertainty propagates, propose a methodology to model, and quantify the uncertainty associated with LCA.

- Improving environmental impact assessment modelling in LCA: although LCA is standardized, its adaptation to each type of system producing electrical energy remains delicate and requires fundamental research in order to remove a number of scientific barriers. Regionalized, dynamical and systemic modelling of environmental impacts, including multi-physics and multi-scale modelling, needs to be developed to narrow distribution of LCA or LCSA, enhance its relevance to support decision-making at local scale and include its possible evolution at various time horizons for prospective purpose.

The call should address:

- the definition of the boundaries of the system and the concept of Functional Unit adapted to each of the chosen uses.
- the assessment of the impact of the lifetimes of the technological system on performance in terms of sustainable development. This involves taking into account the aging of systems through analyses to estimate potential failures that impact the true life of the system.
- the development, beyond the traditional application of LCA as a product-oriented methodology, a new regional LCA-based approach to assess geographically or administratively defined systems.
- the assessment of the consistency of the databases needed to perform an LCA and their influence on the final results through statistical sensitivity analysis.
- Expanding to non accounted environmental and socio-economic impacts, from LCA to LCSA :
  - Integrating environmental and ecosystem impact in LCA to assess the impact of the implementation of an energy system directly in the ecosystem and environment and the modification that will occur. There is therefore a need for the addition of new criteria and metrics describing the impacts of technological systems on the user and/or the ecosystem neglected until now by the LCA standardized method.
  - Encouraging the integration of LCA with other advanced modelling techniques to better incorporate social, environmental, and economic considerations for improved LCSA methodology together with societal LCA (SLCA). Human well-being is a central concept to be defined and articulated in order to integrate societal aspect in LCA and LCSA to promote the improvement of social conditions throughout the life cycle of a product.
  - Linking Life Cycle Sustainability Assessment (LCSA) and Societal Life Cycle Assessment (SLCA) with the Sustainable Development Goals (SDGs): the projects should explore how LCSA can contribute to the achievement of the SDG framework as a whole and further develop the assessment and coverage of interlinkages, trade-offs and prioritization of SDGs in LCSA and SLCA methodologies. They should evaluate by impact indicators defined upstream of the services provided by energy system to the corresponding SDGs (fight against global warming, territorial resilience -compass-, local economic benefits for citizens, create jobs, create pedagogy, etc.), and evaluate by a multi-criteria

decision support analysis (SWOT or MCDA type) the sectors via these SDGs and LCA, SLCA, LCSA.

- Exploring new usage/applications of renewable energy systems for optimizing environmental impacts: New usage/applications of energy systems can be part of nexus (e.g. water-energy-food) that can help minimizing detrimental impacts on the environment while maximizing positive externalities. One example that deserve attention in this call is agrivoltaics. Research still needs to be conducted to assess the negative and positive externalities of agrovoltaics, and identify potential synergies and minimize trade-offs between renewable energy and other ecosystem services. In addition, a careful evaluation of the potential of electrical system coupled with heating systems or with vehicle to grid or to home for environmental improvements is desirable. The call will also welcome new usage and application of energy systems with similar objectives.

#### 5.3.2.2 CP 2 - *Efficient and flexible energy management of systems under massive share of renewables*

##### 1- **Local energy production and demand forecast**

Developing new methods adapted to the energy management on the finer geographical/temporal scales with higher accuracy and taking into account various sources of data, e.g. combining weather forecasts and local measurements. Impact of massive energy and flexibility management on the accuracy of the existing and new prediction methods. Different energy usage and energy vectors should be considered.

##### 2- **New management/control methods of flexibility sources and services** (on local, but also distribution or transport network level).

Design and operation of multi-temporal (from some seconds to some days) and multiscale energy storage systems. Flexibility through the management of multi-energy systems. New flexibility management methods that can accommodate large amount of different flexibility sources and their energy vectors. New methods and pricing mechanisms, flexibility market extension of clearing mechanisms with non-linear market models. Assessing the impact of the imperfect/strategic information on market equilibria and flexibility service providers.

##### 3- **Energy management methods for local communities**

Local communities are taken in the broad sense (neighborhood, city district, industrial zone, island micro-grid...) and management is done under various objectives (self-consumption models, maximization of the share of renewable generation, mutualisation of investment...).

##### 4- **Inter-community energy management.**

Coordination of local communities (with potentially different objectives) and with other actors (including distributed generation and usage, industry, prosumers, aggregators, network level flexibility services...) and including connection between the energy distribution and transport networks. Management of distributed energy systems.

### 5.3.2.3 CP 3 - Technological Solutions for the digitalization of Smart Energy Systems

#### Topic 1: Reliability and security of infrastructures

1. Fail safe modes and redundancy on both hardware and software
2. Tools for modelling of the Smart Grid Architectures (interoperability, flexible operation, Cost Benefit Analysis, security by design...) and tools to assess the compliance of a system of distributed systems, components and processes with regard to international reliability and security standards
3. Consumer data protection and users' privacy preservation, privacy-preserving energy trading (multi-actors energy trading in several contexts).

#### Topic 2: Cyber-Physical Systems distributed architectures

1. Continuum Cloud-Edge-Devices, distribution of intelligence, new specific advanced ICT (Information and Communications Technology) functions and real-time distributed database
2. On the fly data processing for specific/related communication networks and learning on the edge for real time reaction
3. Secure and privacy-preserving federated learning for real time attacks' detection and securing edges/end devices for energy Cyber-Physical Systems

#### Topic 3: Easy deployment and materials

1. Digital control and communication virtualized for easy deployment, consistent and inter-connectable software components, model driven system engineering to enable dynamic reconfiguration
2. High performance infrastructure for both control and protection specific features (considering the environmental impact of this infrastructure), low cost infrastructure for large scale coordination (Service Level Objective about latency and/or reliability)

#### Topic 4: Sizing and design of Digital Twins

1. Tools for modelling and design of the ICT architecture of a digital twin for multi-energy systems (challenge the interconnections of Cyber-Physical components and models in real time, the communication and control interfaces, create joint solvers)
2. Digital twins multi infrastructures for sizing ICT services (e.g. which SLO, which medium term planning for ICT and Energy)
3. Real-time multi-energy digital twin for test, control, training and multi-objective optimization applications

### 5.3.2.4 CP 4 - Contacts with low critical elements

- The overall targets of scarce material reductions should be oriented (principally but not exclusively) toward Solar cells with Ag & In amounts below 2 mg/W and 0.38 mg/W, respectively and  $\eta > 24\%$ . Ideally using a technology that does not require high temperature treatment, nor an aggressive process for reduced environment impact.

The main task identified are:

- Develop Ag-poor electrodes by alternative processes with better material yield, by silver substitution partial or total. Criteria of achievement will be based on above material usage mg/W. Beginning TRL2/3, End TRL3/4.



- Develop In-poor high efficiency solar cells by alternative processes with better material yield, by In substitution partial or total. Criteria of achievement will be based on above material usage mg/W. Beginning TRL2/3, End TRL3/4.
- Research on direct contacting of thin active layers by metallic electrode. Using experiments and modelling, develop specific interfaces and soft deposition approaches. Beginning TRL1/2, end TL3/4. Evaluate scarce material reduction (mg/W saved) vs cell performance.
- Develop innovative thin layer stacks (meta materials?) that combine TCO (In-poor) and Dielectric with electrical/optical properties adapted to solar structures. Beginning TRL1/2, End TRL 3/4... Evaluate scarce material reduction (mg/W saved) vs cell performance.

#### 5.3.2.5 Summary of Call for Proposals

Call for proposals	Challenges	Expected impacts
CP 1: Environmental integration	1- Assessing environmental damages 2- Dynamic ACV	<ul style="list-style-type: none"> <li>• New methodologies for LCA are developed</li> <li>• Cases studies</li> </ul>
CP 2: Efficient and flexible energy management of systems under massive share of renewables	1- Take into account the interplay of different energy vectors and usage, different distributed energy prediction and control methods, the feedback of the local decisions on the overall system.  2- Achieve a flexibility management, incl. storage, to guarantee the system stability.	<ul style="list-style-type: none"> <li>• Ability of new prediction and energy management methods to integrate of all flexibility sources on the distribution network level and counterbalance the variability and intermittence of renewable generation</li> <li>• Ability to address multi-stakeholders energy projects involving multi-criteria decision analysis.</li> <li>• Ability of policy designs and regulatory frameworks to allow market uptake of new stakeholders.</li> </ul>
CP 3: Technological Solutions for the digitalization of Smart Energy Systems	1- Achieve high reliability and low latency service level objectives  2- Achieve intrinsic properties of ICT infrastructures for smart energy system such as transparent deployment and upgrade, perturbation proof, multi-infrastructure awareness	<ul style="list-style-type: none"> <li>• Ability of the deployed middleware on physical devices and simulated equipment to support distributed intelligence for smart energy systems</li> <li>• Reliability and latency performances of the proposed architectures</li> <li>• Ability of the digital twin to give a virtual view in real time of smart energy systems</li> </ul>
CP 4: Contacts with low critical elements	1- Metal grid for charge collection with low critical materials 2- TCL with low critical materials	<ul style="list-style-type: none"> <li>• Silver-free metal contacts</li> <li>• Indium free TCL</li> </ul>

### 5.3.3 Calls for Expression of Interest

#### 5.3.3.1 *CEI 1 - Social science and humanities issues on advanced technologies for energy systems*

- Technical, legal, economic, and sociological issues related to the new decentralized ways of producing and consuming energy
- Principles and conditions of the balance between renewable energy generation and consumption at different scales of the grids.
- Role and limits of the new energy use (mobility, communities, flexibility, etc.) in order to improve the energy system: overall use of the various energy vectors (gas, heat, biomass, electricity), integration of intermittent energies and balance of power systems.
- Energy scenarizations that take into account ethical and justice issues, public perceptions, dynamics of adherence and the conditions for organizing public debates on the technical and economic scenarios of energy production, distribution, and consumption.

#### 5.3.3.2 *CEI 2 - Resilience of electrical grids with massive renewables*

- To predict rare weather climatic events in a changing climate, identify possible critical scenarios of compound weather events which can put at risk energy production at a regional scale: extract data from global and regional climate models, perform bias corrections and downscaling to derive the relevant variable to model the energy capacity, its fluctuations and the possible hazards of a network based on renewable power generators.
- To characterize, model and simulate the impact in the electrical grid of these predicted events and how the massive share of renewable power generators may impact the blackout risks.
- To analyze historical data and past blackouts on similar electrical grids in order to validate to models developed.
- To produce blackout propagation scenarios and estimate their probability of occurrence, to identify scenarios whose probability of occurrence is significantly increased by massive introduction of renewable energy.
- To produce blackout propagation scenarios and to investigate the social and economic consequences of a blackout, and the influence of the market on the blackouts.
- To optimize realistic and fair recovery plans through technical reconfiguration strategies, for selected blackout scenarios, revisit investment strategies and market regulation to account for these new recovery plans.

#### 5.3.3.3 *CEI 3 - Low carbon footprint and recycling PV Module*

- The new encapsulation materials may be made as much as possible with “green chemistry” approach and essentially from bio-sourced or recycled materials and their implementation will not require the use of toxic solvents.
- Reduced temperature processes are required to limit the total energy consumption for the PV module fabrication and to be compatible with photovoltaic devices.
- The recycling and the life cycle of the newly designed encapsulant films will be considered

#### 5.3.3.4 *CEI 4 - Advanced Intelligent PV Module*

- Integrated sensors of performance related quantities (e.g. temperature, current, voltage) using possibly, but not limited to, thin film solar cell technologies.

- Design , realization and integration of switches TFTs, diodes adapted with existing connectors and new PV modules
- Optimization of the module interconnection design as series/parallel/matrix with evaluation of gains due to smart interconnect management
- Early stages of signal processing and power management

#### 5.3.3.5 CEI 5 - reliability of advanced solar cell technologies

- *In situ / operando* characterization tools where properties of the materials, interfaces, solar cell devices, can be tracked under relevant stressors (electrical, optical, thermal, environmental, mechanical, chemical) and combinations of these.
- Complementary *ex situ* characterization that can be performed at various stages of degradation, up to failure and post-failure analysis.
- Multiscale numerical modelling. It consists on one hand of theoretical calculations (*ab initio*, Monte Carlo...) to study the stability of materials and interfaces. On the other hand, numerical modelling based on data analysis from characterizations, including innovative algorithms and procedures, with potentially help of artificial intelligence can also be proposed.

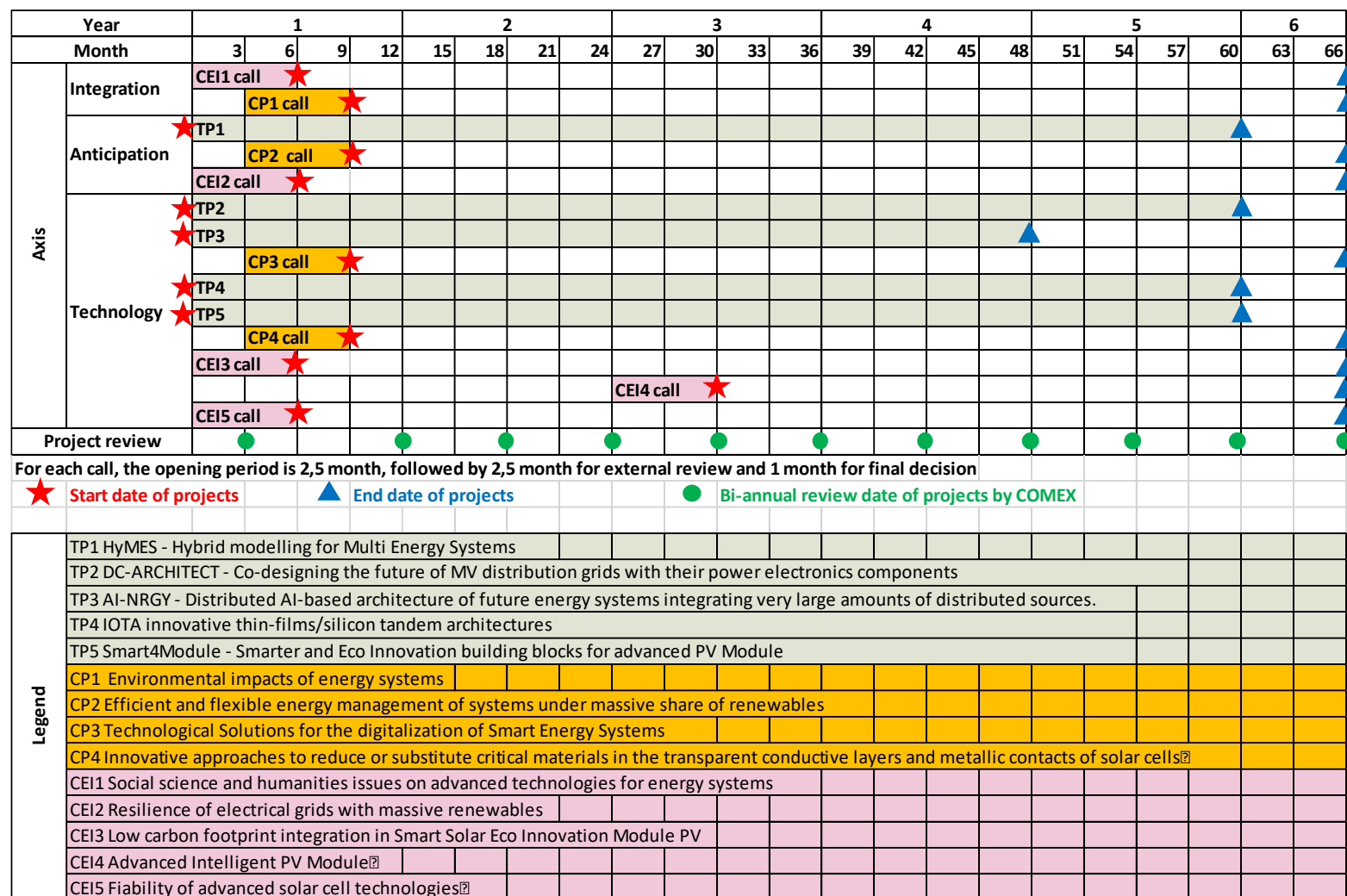
#### 5.3.3.6 Summary of Call for Expression of Interest

Call for Expression of Interest	Challenges	Expected impacts
CEI1 Social science and humanities issues on advanced technologies for energy systems	1- An efficient articulation between generation, grids and new energy uses at all spatial and time scales. 2- Integration of local energy communities into the energy system 3- To solve ethical and justice issues and the need for public debates raised by the energy transformation 4- A continuous dialogue between engineers and researchers in humanities and social sciences	<ul style="list-style-type: none"> <li>• Ability to understand and assess the political, social, economical, spatial dynamics of the energy transition and its links with the technological choices</li> <li>• Ability to provide energy scenarization that take into account ethical and justice issues and the need for public debates</li> </ul>
CEI2 Resilience of electrical grids with massive renewables	1- Developing new techniques that provide relevant representation of extreme weather events to derive climate hazards for wind and solar resources 2- Understanding the events that increase the vulnerability of the electrical grid as well as proposing technical or strategic solutions to prevent major incidents 3- Developing systemic risk analysis methods that integrate weather events, hardware failures and customer behaviors	<ul style="list-style-type: none"> <li>• Ability of proposed predictive and prescriptive models and solutions for assessing and enhancing the resilience of future energy systems,</li> <li>• Ability of the proposed framework to couple multi-scale, multi-disciplinary inputs from climate studies, power engineering, risk analysis and optimization works</li> </ul>

	<p>to identify most important dysfunctional interdependencies, and the scenarios to be studied</p> <p>4- Solving recovery plans optimization problems that will correspond to robust optimization problems.</p>	<ul style="list-style-type: none"> <li>• Occurrence probabilities of high-impact scenarios</li> <li>• Order of magnitude of the impact of massive use of renewable energy power plants on the system resilience.</li> </ul>
<p>CEI3</p> <p>Low carbon footprint and recycling PV Module</p>	<p>1- Developing new encapsulation materials that are sustainable</p> <p>2- Low temperature processes are required to limit the total energy consumption for the PV module fabrication and to be compatible with photovoltaic devices.</p> <p>3- The recycling and the life cycle of the newly designed encapsulate films should be considered</p>	<ul style="list-style-type: none"> <li>• Green chemistry approach, (no toxic solvents is used), sourcing essentially from bio-sourced or recycled materials provide a competitive advantage to sustainable PV made in Europe</li> <li>• Low thermal Budget of the envelope reduces the CO<sub>2</sub>/kWh of PV</li> <li>• New envelopes can be used for emergent PV materials (Perovskites, OPV, ...)</li> </ul>
<p>CEI4</p> <p>Advanced Intelligent PV Module</p>	<p>1- Interface and monitor PV cells with sensors and switches,</p> <p>2- enhance optimal performances of PV modules,</p>	<ul style="list-style-type: none"> <li>• Improved efficiency at the module level that to better management of shadowing</li> <li>• longer use of PV modules</li> <li>• Preventive maintenance</li> </ul>
<p>CEI5</p> <p>Reliability of advanced solar cell technologies</p>	<p>1- In- situ / operando characterization tools where properties of the materials, interfaces, solar cell devices, can be tracked under relevant stressors (electrical, optical, thermal, environmental, mechanical, chemical) and combinations of these.</p> <p>2- Complementary ex situ characterization that can be performed at various stages of degradation, up to failure and post-failure analysis.</p> <p>3- Multiscale numerical modelling for predictive ageing</p>	<ul style="list-style-type: none"> <li>• New tools that can be developed with equipment suppliers and become a reference in the field</li> <li>• Predictive models for ageing</li> <li>• Approaches for accelerated testing</li> </ul>

## 5.4 Planning

The Gantt chart summarizes below the proposed launch dates of the CEI, CP and TP as well as the durations of the actions envisaged under the PEPR.



## 5.5 Overview of requested resources

### 5.5.1 Human resources

The breakdown of hired Ph-D and Post-Docs are presented in the table below.

Partner	CEA LITEN	CEA LIST	CEA IRAMIS	CEA ISAS	LAAS	INL	C2N	IMN	IMS	LRCS	GEEPS	FEMTO-ST	LEMTA	SATIE	AMPERE	IES
number of Ph-D	10	1	1	1	1	3	1	2	2	1	2	2	1	1	2	1
number of Post-Docs (eq. 12 months)	0	1,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Partner	ISIR	G2ELAB	IRIT	GEPEA	LCPO	IPVF	XLIM	LAPLACE	L2EP	INRIA Paris	PERSEE	TOTAL
number of Ph-D	1	2	2	1	1	4	1	2	2	2	2	52
number of Post-Docs (eq. 12 months)	0	0	2	4	0	0	0	0	0	0	0	7,5

### 5.5.2 Financial resources

The financial resources by entity is presented below:

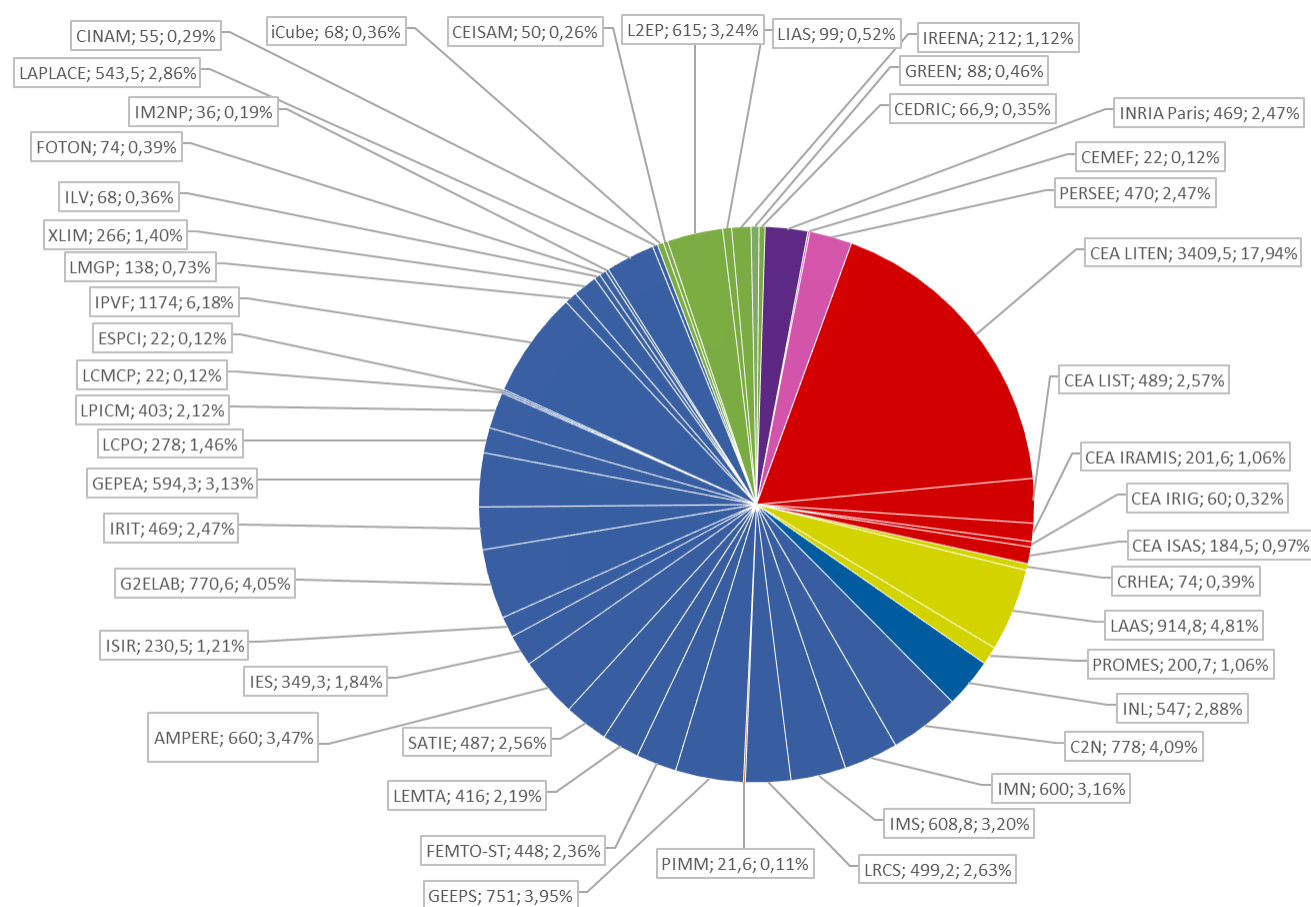


Figure 19 : financial resources by entity and type (blue : joint CNRS-University research unit, red : CEA, yellow: CNRS unit; dark purple: INRIA, green: university unit; pink: MinesParisTech unit)



## 5.6 Request for additional funding

The present strategy did although addressing a major challenge, spanning over many fields of science and technology (Humanities and Social Sciences, Environmental sciences, Electric and more widely energy grid, Photovoltaics, data sciences...), did not benefit from opportunities to invest in equipment (*Equipex*). The priority was set on existing platforms and technologies for a quick start, but additional equipment would be highly desirable to keep the initial impulse.

These could not be covered by the present funding, and are listed below:

- high-throughput-screening for new PV materials
- Operando testing of Photovoltaic cells and minimodules
- Interoperability of power system facilities at national level.

## 6 RISK MITIGATION at PROGRAMME LEVEL

Every targeted project will define their own risk mitigation plan. The Executive committee will ensure that research is challenging and appropriate, project monitoring is adequate, risks are identified, appropriate measures are proposed when needed, milestones are passed and project objectives are met.

At program level, the mitigation plan is as follows (*Table 2*):

*Table 2 : risk mitigation plan at Programme level. Scale: 1= low; 4 = high.*

No	Description	Likelihood	Consequences	Mitigation strategy
<b>R1</b>	Delays in PhD or Postdoc recruitment.	3	3	Projects' tasks will start with internships
<b>R2</b>	Unavailable data for research in SHS, environment of energy networks	3	4	1/ Projects' works will start with open source data or data already published in papers 2/ Unavailable data will be asked to our industrial partners
<b>R3</b>	Expected results are not reached	2	3	1/ Identification and analysis of the unsolved issues 2/ Revision of the planning and revision of the projects objectives 3/ projects will be follow by a large community (academic, ANR ... and industrials). Risks/impacts will be identified as soon as possible with the project managers concerned. Back-up solutions will also be identified in case of failure.
<b>R5</b>	Achieved results are not easily transferrable for helping France to compete in future markets	3	1	1/ Identification and analysis of the innovation issues, including contacts with SATTs and other valorization agencies 2/ Revision of the research goals, in concertation with industry experts.

<b>R6</b>	International dependence or increasing scarcity of raw materials	2	2	This point does not directly concern the research phase but the industrialization phase. However, the coordination of the program will take into account this aspect during the various project reviews and the evolution of the geopolitical context on the additional constraints in case of transfer of innovative solutions to the pre-maturation / maturation phases (additional constraint/risk)
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## 7 EQUAL OPPORTUNITY AND OTHER HUMAN RESOURCES ISSUES

A great attention will be paid to the constitution of the executive committee, in order to respect interdisciplinarity, to make sure that experts have well understood the PEPR strategy and to keep the gender balance.

The PEPR will ensure that candidate selection and recruitment procedures are open, transparent and internationally comparable. The organisms abide by the H4R policy of the EU. The pilots are convinced that the presence of women in the research community is very important as models for students to develop their ambitions and believe in their capabilities. To encourage women to apply for a PhD, the best practices of actors involved in the gender issue in science will be consulted, such as the Association "Femmes & Sciences" which is the French member of the European Platform of Women scientists. The employment contract of PhD students includes maternity and paternity leaves.

The parity of the Executive Committee will be respected. The Executive committee will monitor the projects to ensure that a well gender balance selection of the PhD students (please refer to KPIs)

The promotion of early carrier researchers is also an important aspect of the PEPR.

International cooperation is an essential part of an ambitious scientific program. By design of the PEPR global strategy, there is no financial support of foreign teams, yet, missions and exchanges are possible. Moreover, strengthening the research base of French teams will make them more relevant and able partners for international cooperation.

## 8 GOVERNANCE and MANAGEMENT

### 8.1 Governance

In order to promote the smooth running of the program, CEA and CNRS will create a Program Chair as well as an Executive Committee (COMEX) composed of qualified representatives of each organization.

#### 8.1.1 The Program Chairs

Two program chairs will be appointed by CNRS and CEA. To date, Alain Schuhl (General Director of services at CNRS) and Philippe Stohr (Director of Energies at CEA) are proposed as Program Chairs.

The principal tasks of the Program Chairs shall be:

- to ensure that the collaboration between CEA and CNRS goes smoothly, and to arbitrate points unable
- to validate the annual review of the Program

- to validate the potential reorientation within the Program,
- to validate the exploitation plan (industrial transfer, Start-Up creation...)

It will meet once a year.

### 8.1.2 Executive Committee (COMEX)

It will be led by the two Programme Directors (Jean-François Guillemoles for CNRS and Philippe Azaïs for CEA) and two Deputy Programme Directors (Nicolas Retière for CNRS and Guillaume Ravel for CEA) appointed by CEA & CNRS : together with 3 additional appointed representatives of both organizations covering scientific and non-scientific activities. More precisely, the composition will be as follows:

- One representative in charge of international activities
- One representative in charge of the dissemination/communication activities
- One General Secretary

The COMEX will be completed by scientific advisors covering the different areas of the Programme.

CSTP will include scientific advisors from various scientific backgrounds and institutions to ensure representativeness of relevant points of view

Program chairs are the natural channel to resolve such potential differences, as they have been until now.

Two senior researchers coming from two distinct organizations, which may be CEA or CNRS, but also other organizations will advise each of the three research themes of the PEPR. The following breakdown is proposed:

Topic	Representative organizations
Integration - Support the transition to a global energy system with a controlled environmental and societal impact	CNRS/Univ. & CNRS/Univ.
Anticipation - Anticipate energy system trajectories	INRIA & CEA
Technology 1 - Flexible and resilient networks	CNRS/Univ. & CEA
Technology 2 - Ecofriendly and efficient PV	CNRS/Univ. & CEA

The scientific advisors will be appointed by their home organization

Main tasks of the scientific advisors:

- Organization of workshops within their axis gathering targeted projects, and projects issued from the Call for Proposals (at least once a year)
- Participation to the COMEX

The principal tasks of the Executive Committee (COMEX) shall be:

- to ensure the smooth running of the Program

- to propose a ranking to the COSTRAT (TASE French inter-ministerial committee) of the projects issued from the Call for Proposals, on the basis of the recommendations provided by the ANR's Jury.
- to propose potential reorientations of the projects
- to ensure effective communication and exchange of technical and/or non-technical information related to each Project;
- to prepare the annual review to be presented to the Strategy Committee
- to promote international exchanges of scientists
- to establish a communication plan

The Executive Committee will meet at least every two months at the beginning of the programme and twice a year once launched. The ANR will be a permanent guest of the COMEX.

### 8.1.3 Strategic Committee (COSTRAT)

The COSTRAT is the inter-ministerial TASE French Governmental Committee. The COSTRAT includes (but not limited to) members from SGPI, DGE, DGRI, DGEC, ADEME, BpiFrance and ANR. It will check that the PEPR strategy is well aligned with the French national strategy on Advanced Technologies for Energy Systems (TASE).

## 8.2 Animation, communication and dissemination activities

A dissemination Plan to maximize the potential impact of the project results will be developed. It will rely on the following actions:

- creation and continuous update of a public website portal providing a press package containing downloadable short explanatory information (project sheet), press releases, photographs, videos, project flyer(s) and e-newsletters with easily digestible information. A private, secured part of the website will be used to manage all the confidential documents and communications.
- creation and continuous update of social networks account to make the PEPR TASE visible
- launch of a periodic newsletter devoted to the research community and the relevant industry actors
- presentation of the Program results at high-level international conferences
- creation of a graphic kit and tools to be used by PEPR members (PowerPoint presentation, banners, leaflet, kakemonos...)
- organization of an annual scientific seminar for communicating the latest results and the achievements of the Program with the presence of the COSTRAT, the CSTP, the Advisory Industrial Club, and researchers from the TASE community

In addition, a special attention will be paid to the popularization of the activities and results of TASE, through participations and organization of public debates on the place of TASE in society.

Finally, joint symposia with other PEPR with whom synergies have been identified (e.g. environmental aspects, LCA, Data ...), such as PEPR on “Batteries”, “Recycling”, “Decarbonization of Industry”, “Cloud”, “5G”, “Electronic”, “Cybersecurity”...

### 8.3 Exploitation plan

Exploitation will encompass the results of the project and their pathway to the market. The exploitation plan will be based on the early identification of exploitable results and an exhaustive market analysis. To promote exploitation, brainstorming sessions will be held periodically to encourage the filing of patents and creation of start-ups.

Regarding IP management, Project consortium agreement is the standard for IP management at project level. The exploitation of intellectual property will be carried out in close link with the bodies in charge of industrial exploitation (SATT, ITE, *CNRS Innovation*, *CEA Valorisation* ...). Similar strategy is applied for data management plan.

#### *Advisory Industrial Club*

In order to promote technological transfer to industry actors operating in France, an “advisory industrial club” (AIC) will be created upon proposition of the Executive Committee. It will be composed of key economic actors in the field of Advanced Technologies for Energy Systems (TASE), such as for instance CIGRE representatives. More precisely, the mission of the members of this club will be to assist, advise the scientific directors with respect to the potential of valorization and technological transfer of the results issued from the Program to the economic world. This “club” will be invited to programme review. In addition, two special “innovation day” will be organized the program to promote discussions around potential transfers. Industrials will also have the opportunities to present their roadmap, and the key challenges they have to face.

Communication of the program results to industry will be organized on a regular basis following program review meetings:

- Regular information to CSF and exchanges have been planned during the concertation that was made during the building of the program. Once a year seemed like a good periodicity
- Relation to SATT and valorization in organisms:
  - o A regular meeting will be held with industry and government representatives to anticipate what may be the subject of subsequent pre-maturation/maturation projects with industry.
  - o In addition, representatives of the organizations (CNRS, CEA) will be present in the juries of these higher TRL projects.

### 8.4 Management

The program management will be organized by the program directors and co-directors, with the help of a small team who will prepare the monitoring of milestones, the reporting of budget execution and the reviews. At the end of each year a progress report will be produced. The global management structure of the program is given in the following diagram (*Figure 20*).

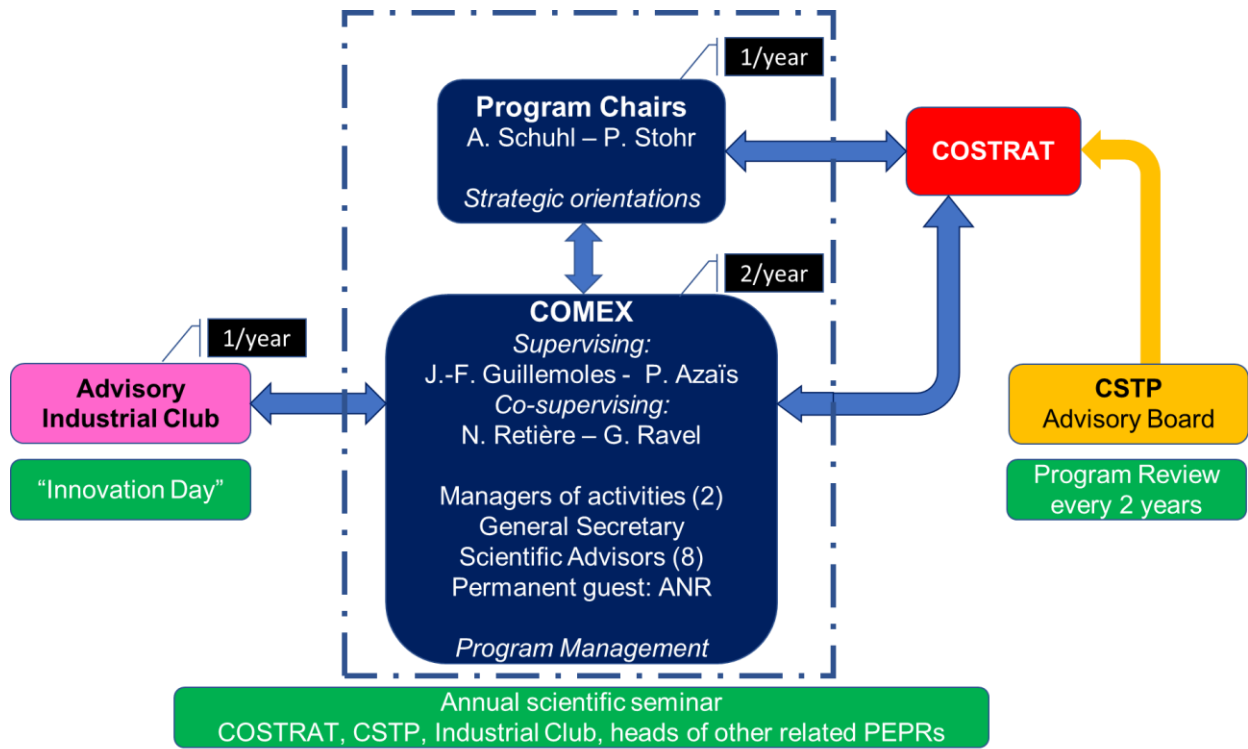


Figure 20 : Global management structure of PEPR TASE



The management Gantt is shown below.

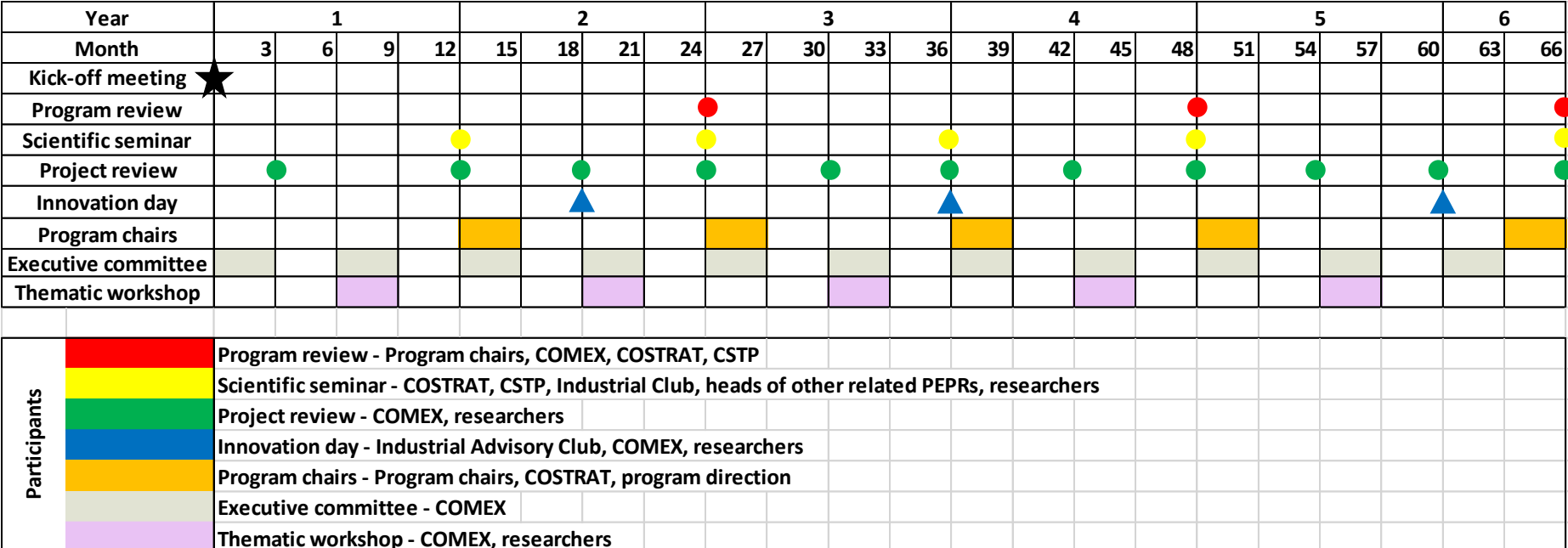


Figure 21 : Management Gantt

## 9 EXPECTED OUTCOMES of the PROGRAMME

### 9.1 Expected outcomes on Social science and humanities issues (Int.1)

- Provide analytical frameworks and models to understand and assess the political, economic, social, spatial, legal dynamics of the energy transformation
- Provide a set of practice analyzes based on living labs observations or field surveys
- Propose energy scenarios that take into account ethical and justice issues, public perceptions, dynamics of adherence and the conditions for organizing public debates

### 9.2 Expected outcomes on environmental impact (Int.2)

#### 9.2.1 Improved LCA methodology:

- Identify uncertainty sources in the LCA process, determine how uncertainty propagates and propose a methodology to model and quantify, as far as is possible, the uncertainty associated with LCA.
- Improve the environmental impact assessment modelling in LCA: develop regionalized, dynamical and systemic modelling of environmental impacts to enhance its relevance to support decision-making at local scale and include its possible evolution at various time horizons for prospective purpose.

#### 9.2.2 New usages/applications of renewable energy systems

- Propose new usage/applications of renewable energy systems that optimize environmental impacts: minimizing detrimental impacts on the environment while maximizing positive externalities.

### 9.3 Expected outcomes on Networks (Ant. and Sys-Tec.)

#### 9.3.1 New methods for a controlled energy transition

- Proposal of a hybrid model of multi energy systems with an innovative combination of physic-based models and learning models. This model will be faster than co-simulation and could be used for optimizing the system operation and design.
- New advanced control and forecast strategies for energy systems with a massive share of local energy resources of any sizes and technologies
- Predictive and prescriptive models for enhancing the resilience of future energy systems, taking into account technical and socio-economic issues
- Open source models, use case and benchmarks

#### 9.3.2 Specifications and candidate architectures for MVDC distribution networks and their power electronics converters

- Develop MVDC (Medium Voltage Direct Current) innovative design solution to integrate effectively renewable energy sources, thus contributing to an affordable pathway to archive climate neutrality goals
- Definition of candidate architectures for MVDC distribution grids (topology, voltage set-points, operating modes)

- Specifications for power electronics converters used as grid interfaces and source connections
- Initial contribution to an extended grid code for MVDC distribution grids
- Definition of candidate structures, closed-loop control and health monitoring strategies for grid-interface power electronic converters
- Delivery of new methods for stability analysis, fault detection and localization of mixed AC/DC grids with a massive share of power electronics converters.
- Ensure qualification of design and system solution through validating, demonstrating, and evaluating MVDC solutions via case studies and lab tests (ex: HIL).

#### 9.3.3 Key digital technologies for smart energy systems

- Deployment of middleware on physical devices and simulated equipment to support edge forecasting
- New edge computing architectures supporting distributed intelligence for smart grids
- Production of reliable and resilient distributed intelligent solutions for collaborative forecasting, optimization, real-time control
- Formal methods for designing the monitoring infrastructure with guaranteed system observability.
- Virtualization methods and techniques for Plug&Play communication and control of the energy system devices
- Tools for digital twin of a smart energy system
- Open source software developed for data and service deployment

#### 9.3.4 Accelerating the innovation cycle

- Integration of the developed technologies and methods by industrial actors, DSO (Distributed System Operators)/TSO (Transmission System Operators), large-scale integrators, technology providers.

### 9.4 Expected outcomes on Photovoltaics (PV-Tec.)

#### 9.4.1 Efficient and sustainable solar cells:

- Invention and demonstration of innovative thin-films/silicon tandem architectures
- Proof of concept and development of key breakthrough technological building blocks (photon management, material stacking, interfaces, and carrier extraction technologies) to enable novel architectures compatible with the efficient materials already available
- New contact materials (transparent conducting layers, grids) with low or excluding critical element are available for sustainable photovoltaic production

#### 9.4.2 Low environmental footprint and innovative photovoltaic modules:

- Deliver innovative and more eco-responsible building blocks to prepare the next generation of modules and tandem devices having (i) a higher level of integration including the printing of interconnections and bypass diodes and (ii) novel possibilities of PV module integration in our environment with tunable level of coloration/transparency for social acceptance and new opportunities of integration.
- Deliver a new generation of low environmental footprint and reliable encapsulation (sourcing of envelope materials, reduced energy in processing, disassembling process

of the envelope that enables recovery), that should moreover be compatible with fragile devices

- Demonstration of the Integration of smart functions for next generation of PV module (reconfigurable connections, signal processing...)

#### 9.4.3 Accelerated innovation cycle for innovative photovoltaic devices:

- Deliver quantitative assessment of the degradation of new technologies for high efficiency solar cells
- Develop advanced testing equipment for both *in-situ/operando* and *ex-situ* characterization
- Deliver predictive ageing models based on characterization data and numerical modelling.
- Propose accelerated testing procedures for the new technologies for high efficiency solar cells

## 9.5 KPI - Key Performance Indicators

The following metrics will be used to monitor the progress of the programme. This first list will be consolidated at the beginning of the programme, especially on the social and environmental domains. These metrics will be complementary of more specific indicators defined projects by projects to measure their own performance. These are measured by number of items, unless specified otherwise.

Domain	Type	Metrics
Program management	Research activity and structuration	Researchers involved into the projects Recruited PhDs and postdocs
	Outcomes	High level publications (open science) International conferences Keynote speeches Prizes (best paper awards ...)
	Impacts	Patents Created startups Cooperation agreements issued from the programme results Public research funding issued from the programme results Open tools, databases or benchmarks issued from the programme Companies using at least one invention of the project New testing procedures used in collaboration with companies for accelerated development of technologies
Society	Social KPIs	Identification of potential actionable decisions that improves social appropriation of energy services
Environment	Environmental KPIs	Reduction of Carbon footprint, environmental and of landscape impact, from the models Diffusion and adoption of some of the new LCA methodologies
Resilient and flexible network	Technical KPIs	Hosting capacity of renewable energy sources Hosting capacity of distributed energy resources, electric vehicles and other active loads

	These metrics will be provided by the projects. They will be estimated by simulation, comparing the values obtained on reference use cases, at the beginning and at the end of the project.	Increased system flexibility (amount of generation or load that can be shifted temporarily) Improved Power Quality (voltage variations, harmonic distortion) Reduced network losses Increased system resilience (ability to absorb a critical event) Reduced energy curtailment Increased asset lifetime
Efficient photovoltaics	Technical KPIs	Tandem devices thin film on c-Si with efficiency > 30% and reduced environmental footprint Capacity to propose new technologies for tandem that lead to successful answers to EU call and collaborations with Industry At least one alternative to ITO and Ag contacts for tandem devices Dependence on critical materials halved at least Environmental footprint halved on modules Smart module with sensors and reconfigurable connections Accelerated innovation cycle by early on incorporation of reliability issues in the R&D by: development of new in-situ/operando and ex-situ survey tools and accelerated testing for improved reliability prediction

Additional KPI will be monitored :

- Number of PhD students co-supervised by multidisciplinary teams
- Number of paper cosigned by multidisciplinary teams
- Number of research units involved in the program
- Number of research teams in social sciences and humanities involved in the program
- Number of outcomes that are identified and selected for further innovation works
- Gender balance in hiring and in responsibilities in projects (WP)
- Career opportunities of young researchers

## 10 INFORMATION TO CDEFI, UDICE, CGE, CPU, CSF-NSE

The project was presented to representatives of France Universités<sup>108</sup> (Xavier Py and Abdou Djouadi), CGE<sup>109</sup> (Bruno Lacarrière and Yvan Bonnassieux), CDEFI<sup>110</sup> (Bruno François) and UDICE<sup>111</sup> (Guy Clerc) on January 7<sup>th</sup> and February 4<sup>th</sup>.

CSF-NSE<sup>112</sup> was met February 23<sup>rd</sup> 2022. PEPR were invited to give a webinar to disseminate information regarding the programme after the kick-off meeting.

<sup>108</sup> France Universités, [www.franceuniversites.fr](http://www.franceuniversites.fr)

<sup>109</sup> CGE : Conférence des Grandes Ecoles. [www.cge.asso.fr](http://www.cge.asso.fr)

<sup>110</sup> CDEFI : Conférence des Directeurs des Ecoles Françaises d'Ingénieurs, [www.cdefi.fr](http://www.cdefi.fr)

<sup>111</sup> UDICE, [www.udice.org](http://www.udice.org). Udice, French research universities Organisation

The Udice Group universities are characterised by their ambitions and the deep transformations they have embarked on, over the last 10 years, in order to fulfil their public service missions. Udice is a group working for excellence in research, performance in higher education and the development of attractive innovation ecosystems in France and across Europe.

<sup>112</sup> CSF-NSE : Comité Stratégique de Filière – Nouveaux Systèmes Energétiques, [www.systemesenergetiques.org](http://www.systemesenergetiques.org)

## 11 RECOMMENDATIONS FROM ITE

ITE<sup>113</sup> were involved in discussion and informed during the preparation of this document.

FEM (France Energies Marines) was met January 26<sup>th</sup> 2022. SuperGrid was met February 10<sup>th</sup>. INES2S and IPVF were met February 11<sup>th</sup> 2022.

Our program and ITEs are complementary. PEPR will address low TRL research (TRL 1 to 4) that will help structure the research community and possibly allow discussions with ITEs when moving from lab proof of concepts to industrial developments. PEPR will focus on advanced methodologies to design and control future energy systems and breakthrough technologies that are not mature enough to be put on markets. We aim at bringing to ITEs and other technology transfer organisms the next generation methods and technologies that they could develop for markets.

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<sup>113</sup> ITE : Institut de Transition Energétique





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M. Bruno BONNELL  
Secrétaire Général pour l'Investissement  
Hôtel de Cassini  
32 rue de Babylone  
75700 Paris SP 07

Villeurbanne, le 18/02/2022

**Objet: Soutien au PEPR de la Stratégie d'accélération « Technologie avancées pour les systèmes énergétiques » (TASE)**

Monsieur le Secrétaire Général,

Dans le cadre de l'élaboration du PEPR de la stratégie d'accélération TASE, Le CEA et le CNRS, missionnés pour sa rédaction, ont présenté à SuperGrid Institute les grands axes qu'ils proposent et leur déclinaison en appels à projet et en projets ciblés.

Cette proposition a nécessité des choix, et SuperGrid Institute manifeste par la présente son soutien aux choix proposés par l'équipe de rédaction, pour le périmètre qu'il maîtrise.

L'équipe de rédaction propose également de nouer un lien permanent avec Supergrid Institute à travers des rencontres régulières et des points d'étapes sur les avancements, particulièrement sur le projet ciblé dédié au MVDC.

Cette suggestion nous paraît indispensable pour que l'ITE puisse s'approprier les avancées générées par ce programme afin de les porter à des niveaux de maturation plus élevés, faisant levier sur ces travaux pour apporter de la valeur aux industriels.

Ce mode opératoire pourrait d'ailleurs être étendu à l'ITE Efficacy sur le projet ciblé de modélisation des réseaux multi-énergies et à l'ITE France Energies Marines pour les travaux sur l'éolien Flottant ; l'ITE IPVF et INES25 semblent être déjà intégrés pour le photovoltaïque, via respectivement l'IPP et le LITEN.

Veuillez agréer, monsieur le Secrétaire Général, l'assurance de toute ma considération.

Hubert DE LA GRANDIERE

***Shaping power transmission***

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**Secrétaire Général pour l'investissement**

Hôtel de Cassini

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**A l'attention de Monsieur Bruno BONNELL**

Palaiseau, le 24/02/2022

**Objet : Soutien au PEPR de la Stratégie d'accélération « Technologie avancées pour les systèmes énergétiques » (TASE)**

Monsieur,

Dans le cadre de l'élaboration du PEPR de la stratégie d'accélération TASE, le CEA et le CNRS, missionnés pour sa rédaction, ont présenté à l'IPVF – Institut Photovoltaïque d'Île-de-France, les grands axes qu'ils proposent et leur déclinaison en appels à projet et en projet ciblés.

L'IPVF souhaite manifester par la présente son soutien aux choix proposés par l'équipe de rédaction pour ce qui concerne son domaine d'excellence, le solaire photovoltaïque. Ceux-ci sont par ailleurs confortés par la feuille de route européenne élaborée en 2021 par l'ETIP PV – European Technology & Innovation Platform for Photovoltaics, baptisée *Strategic Research & Innovation Agenda*.

L'équipe de rédaction propose également de nouer un lien permanent avec l'IPVF à travers des rencontres régulières et des points d'étapes sur les avancements, particulièrement sur le sous-axe technologique 2 « *PV Efficient et Ecofriendly* ». Cette suggestion nous paraît indispensable pour que l'ITE puisse s'approprier les avancées générées par le PEPR et les porter à des niveaux de maturation plus élevés, dans un objectif de transfert industriel rapide.

Nous vous prions d'agréer, Monsieur le Secrétaire Général, l'expression de nos salutations distinguées.

**Roch DROZDOWSKI-STREHL**

**Directeur Général IPVF – Institut Photovoltaïque d'Île-de-France**

**Vice-Président ETIP PV – European Technology and Innovation Platform for Photovoltaics**

Page 1 sur 1

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INSTITUT PHOTOVOLTAÏQUE D'ÎLE-DE-FRANCE

SAS au capital de 14 500 000 €

N° Siret : 539 072 793 00042 - RCS Evry : B 539 072 793 – Code NAF : 7112 B - TVA Intracommunautaire FR 53539072793

[www.ipvf.fr](http://www.ipvf.fr)

## 12 Annex

### 12.1 ANNEX 1: CNRS SKILLS in TASE

#### 12.1.1 Networks @ CNRS-Universities joint research units (UMR)

##### 12.1.1.1 General description

CNRS brings together in joint unit research labs with universities almost 600 permanent researchers (CNRS researchers or associate and full professors from University) working on energy transmission, distribution and storage. Almost 400 researchers work more specifically on electrical energy vector 170 carry out their research in electrical engineering. The research community working on buildings and sustainable cities (about 300 researchers), mobility (500) and socio-technical aspects (500) also studies energy networks. Most of these researchers are hosted in joint research units with universities. They perpetuate the long-lasting tradition of a strong cooperation between basic research and training of engineers and technicians for the energy industry. All these units have many collaborations with small to large companies working in this field (RTE, ENEDIS, EDF, Schneider, Nexans, Atos, Airbus, SNCF, Renault, Supergrid Institute, CEA LITEN, Valeo, Start-ups...).

The skills of these researchers cover many aspects essential for the study and the operation of networks:

- analytical and numerical methods and models for optimal design, control, diagnosis of energy systems
- development of new energy conversion technologies
- testing of technological solutions
- characterization and use of materials for realizing efficient electrical devices and systems

The CNRS research teams host several experimental facilities to test the developed technologies. They include:

- Experimental buildings with renewables sources, active loads, electric vehicle charging infrastructures, supervision centers in Grenoble, Toulouse and Lille
- Hardware-in-the-Loop platforms for prototyping and testing control or protection algorithms in Grenoble, Lyon, Lille ...
- Reduced-scale AC or DC networks for integration test in Lyon, Toulouse and Grenoble
- Experimental platforms for reliability and aging tests in Paris, Bordeaux ...

Electrical engineering is a central activity for energy transition study and promotion. A joint research group CNRS named SEEDS (Systèmes d'Energie Electrique dans leurs Dimensions Sociétales) gathers academic teams from the CNRS, the French Ministry of Research, and other research organizations). It also maintains close links with the other scientific communities concerned by generation, distribution, transformation and use of electrical energy, e.g. the joint research groups MACS for the modelling, analysis and control of dynamic systems and HysPac gathering research teams working on hydrogen and fuel cells.

At national level, SEEDS is the only integrative structure of the 39 electrical engineering labs. Its actions include:

- Scientific animation through workshops and working groups
- Co-organization of the Young Researchers' Days in Electrical Engineering (JCGE)
- Elaboration of prospective documents
- Promotion of structuring initiatives on major scientific challenges

- Building of joint proposals to national and European calls
- Promotion of innovation and technology transfer actions.

*12.1.1.2 Example of facilities that will be used in the programme*

**EPMLAB (L2EP - Lille) - <https://www.epmlab.eu/>**

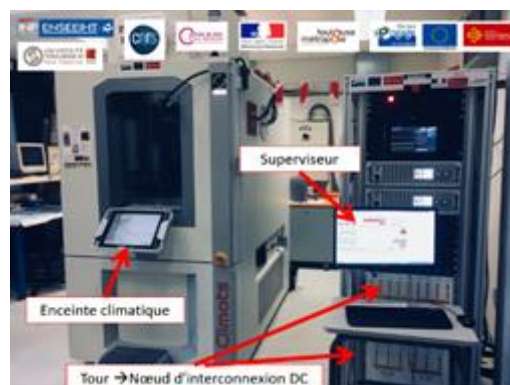
Electrical Power Management Lab is an experimental setup, which comprises various equipment dedicated to the test of electrical devices connected to the grid. The core of this lab is a 7-cores OPAL-RT Real Time simulator, which allows achieving various Hardware in the Loop studies. Associated to some high bandwidth power amplifiers, it is also possible to connect some power devices to the real time simulation environment. Various DC/AC power electronic converters have been developed to be connected to this simulation but the most important development is a 5 kW - 20 levels Modular Multi-Level Converter. A 5-terminal DC network is also available in this lab.

**Experimental platform for microgrids (LAPLACE - Toulouse)**

The Laplace, Université de Toulouse, has an experimental platform for power microgrids (*Figure 22*), interconnected with a battery test bench (*Figure 23*) and a solar PV roof. Built around the concept of Power Hardware In the Loop, this investigation platform allows, in a versatile way, to test various architectures of AC, DC or mixed microgrids, thanks to several buses allowing to interconnect sources (PV (physical or emulated), wind turbines), storage (physical or emulated) and loads controlled and supervised with a real time SCADA.



*Figure 22 : Microgrid facility*



*Figure 23 : Battery test bench*



**PREDIS-MHI platform (G2Elab - Grenoble) - <https://g2elab.grenoble-inp.fr/fr/plateformes/predis>**

PREDIS-MHI centre had been established few years ago in Grenoble to support the research about interconnection of distributed energy resources in the electrical grid and the new uses of energy in buildings. It is a unique platform gathering diverse demonstrators and living labs over 200 m<sup>2</sup> in a building used for teaching and research activities at Grenoble (*Figure 24*).



*Figure 24 : PREDIS-MHI platform in the GrEEN-ER building.*

This platform includes:

- Dispersed generators : PV panels, fuel cell demonstrator, micro gas turbine
- Reduced size power grids for industrial sites or distribution network with their SCADA supervision system
- A real-time system to emulate any kind of device or network of any size with power hardware connections to real devices or subsystems
- A 600m<sup>2</sup> living lab to study new energy uses, the design and management of complex building energy systems

Hardware-in-the-Loop platforms for prototyping and testing control or protection algorithms in Grenoble

Among the various tools to validate research programs, fast prototyping using Real Time Simulator for Hardware-In-the-Loop (HIL) simulations (Opal RT, Typhoon) and Power-Hardware-In-the-Loop testing (PHIL) are used. They allow Grenoble PhD and senior researchers to target specific validations for control and protection. Thanks to top grade materials and long tradition leading to cutting edge experience, Grenoble Hardware in the Loop platform excels in Smart Grid projects.

Reduced-scale AC or DC networks for integration test

Reduced scale distribution network are selected whenever the HIL/PHIL shows limits on the number of devices interacting. Those networks had been built facing various grid situations. One can find among others an industrial reduced scale network (intended to cover EMI issues) and a reduced 1/1000<sup>th</sup> scale distribution networks built to validate self healing and other advanced automation functions for Smart Grids).

**ADREAM (LAAS-Toulouse) - <https://www.laas.fr/public/en/adream>**

Experimental micro-grid dedicated to BIPV applications and mixed LVDC/LVAC micro-grids

The LAAS-CNRS has quite capacities to validate researches on smart-grids concepts by means of its own operational platform including different test benches able to provide experimental results in real working conditions (*Figure 25*). This building can be considered as a BIPV building with different electrical and thermal energies sources and its extensive electrical network LVDC/LVAC able to exchange with classical three-phase grid or work on standalone mode. With its meteorology station, its storage elements and its complex monitoring system, a large scale of research innovations on the development of Intelligent Energy Management solutions based on renewable energies shall be validated.



*Figure 25 : Aerial View of the ADREAM Building*

The building has a surface of 1700 m<sup>2</sup> and it incorporates an installation of 720 m<sup>2</sup> of solar panels, 500 m<sup>2</sup> of experimental area, and 700 m<sup>2</sup> of offices.

**Energy Systems**

The sustainable ADREAM building (*Figure 26*) was designed to set an example by its environmentally-aware approach considering the heating, the air conditioning, the lighting, and the various electronic devices.



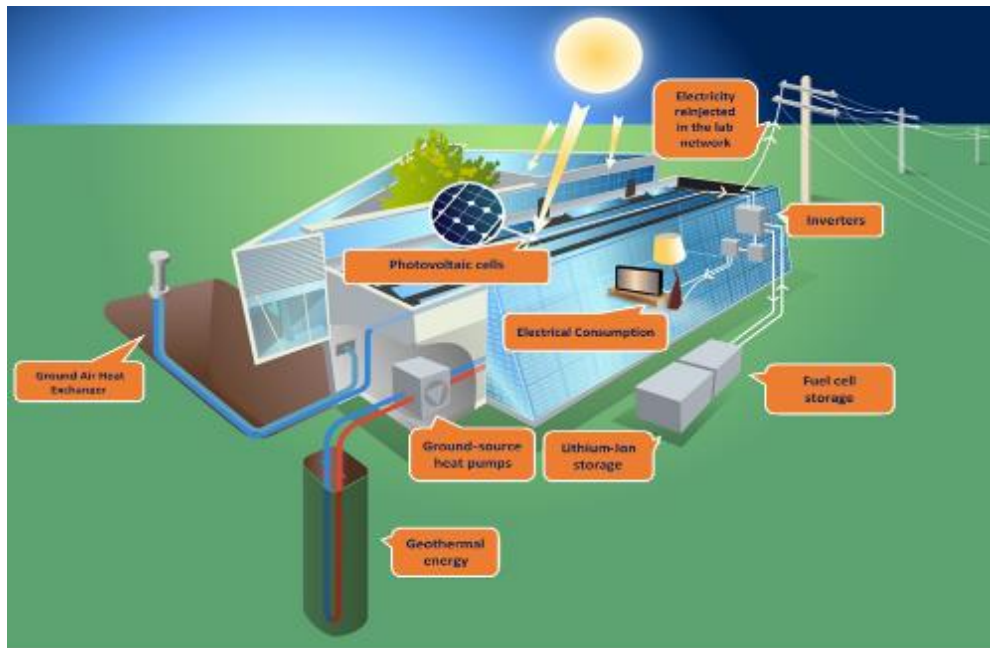


Figure 26 : *Energy Systems installed in ADREAM*

ADREAM is connected to an electrical network, which benefits from a total of 100kWp of photovoltaic energy. In addition, it involves the use of geothermal energy through the installation of three ground source heat pumps (135kW). The hygienic ventilation system is also linked to a ground heat exchanger to minimize the heating/cooling energy needs of the air. The notion of “Intelligent Energy Management” is today able to supervise exchanges between the energy issue from the photovoltaic array, the optimized consumption of this building and the rest of the buildings composing the LAAS-CNRS laboratory through high performance LVAC systems. One of the main objectives behind the construction of this building was to give rise to a grid of optimized energy consumption and production, while achieving periodical states of positive energy, without compromising user comfort.

### **Supervision System and Database.**

ADREAM is an instrumented building which is connected to a control and supervision system. The system allows the registration of measurements for reporting and analysis purposes. The control and supervision is carried out through the software PCVue, developed by ARC Informatique, adapted to the technical specifications of the building. This system is tied to 6500 integrated sensors and various controllers (WAGO, TAC) which regulate the whole installation. The registration of the data takes place periodically with a frequency varying from 1 to 5 minutes, according to the different setup of each sensor. This information is then measured, posted, and registered by the PCVue software. The daily number of data points registered in the database can reach 500000.

The objective of this management system is, on one hand to assure the automatic functioning of the building (thermal and lighting regulation with the possibility of minor variations by the occupants according to their comfort perception), and on the other hand to supervise in real time the operation of the various interconnected equipment for the purpose of a detailed energetic analysis and optimization. The PCVue program allows the surveillance of the intelligent lighting system, the functioning and control of the HVAC (Heating, Ventilation and Air Conditioning) systems, and the supervision of the photovoltaic production along with the electrical consumption.

An example of the experimental campaign of tests done in the adream building dedicated for storage elements behaviors studies is sum up of *Figure 27*.

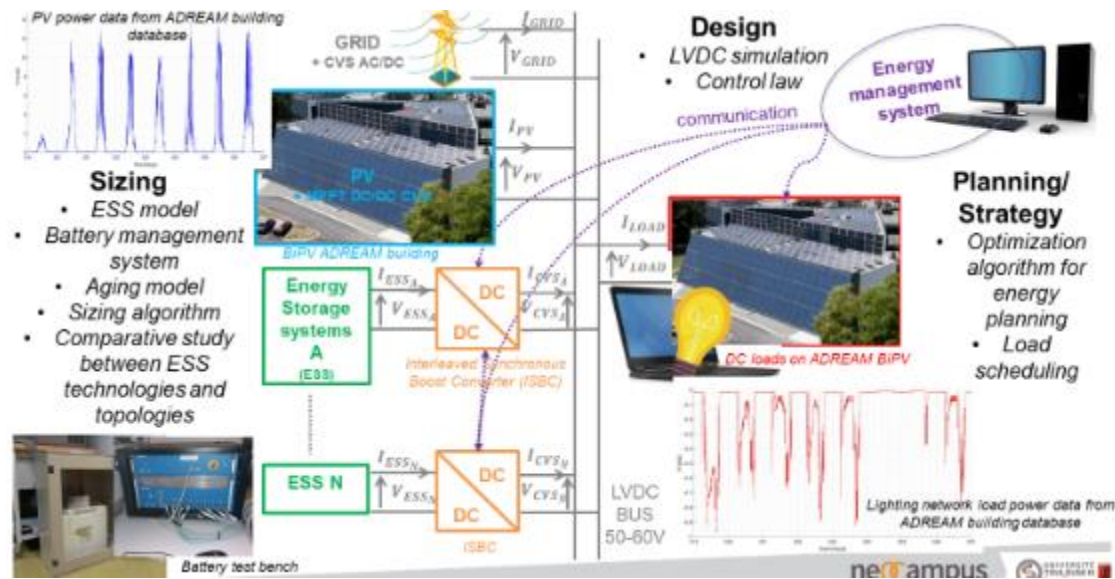


Figure 27 : Campaign of tests done with a simple LVDC micro-grid to study several storage components in real conditions.

### Additional experimental tests benches

For new Wide BandGap components, the LAAS-CNRS recently expanded its experimental capacity with new means of characterizations named « PROOF Platform » (*Platform of Reliability tOOls for Failure analysis dedicated to wide bandgap devices*). <https://www.laas.fr/projects/proof/>

In IMS, experimental platform for reliability assessment allows multi-physic characterizations of power components at different state of health but also accelerated aging tests under elementary and combined stresses. Regarding power semiconductor assemblies, equipment are power device analyser/curve tracer, failures analyser and environmental test chambers. For electric energy storage systems, the Cacyssée platform includes electrochemical workstations with impedance spectroscopy, charge-discharge benches with high current levels, secure climatic chambers, accelerated rate calorimeter, power and management electronics for multi-source systems test.

### 12.1.2 PV @ CNRS-Universities joint research units (UMR)

#### IPVF

IPVF Platform (*Figure 28*) gives access to exceptional scientific services, combining high-tech equipment and researchers' expertise to accelerate photovoltaic research projects (<https://www.ipvf.fr/platform-2/home/>). This platform is accessible to UMRs in the framework of an agreement with the ITE IPVF, with access to over 100 cutting-edge pieces of equipment for characterization and processing, with state-of-the-art capabilities, ranging from standard to advanced equipment in some 3000 m<sup>2</sup> of labs and clean rooms.

On characterization: Morphological, composition, optoelectronic characterization, basic and advanced. Unique expertise: PL spectroscopy imaging.

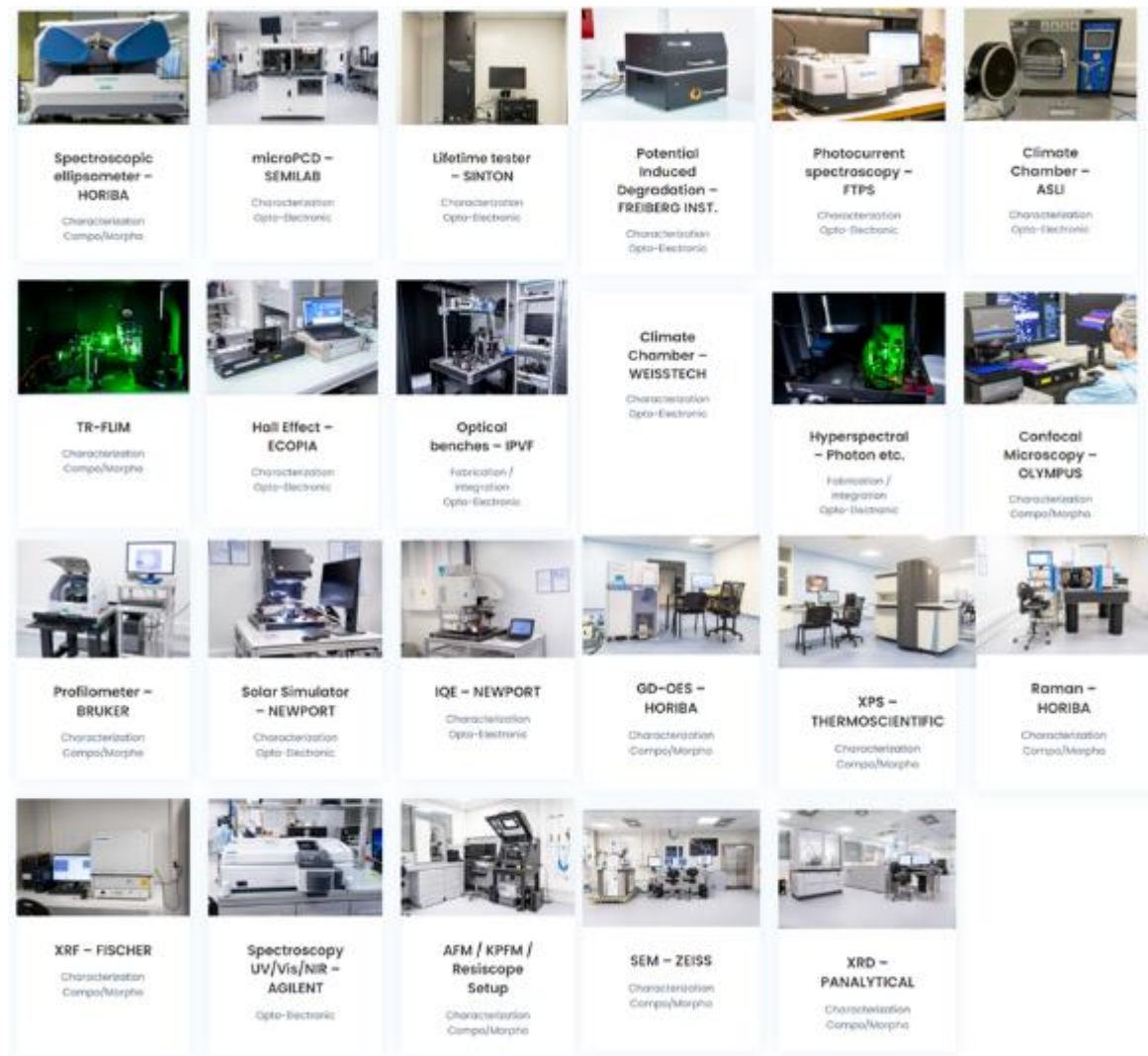


Figure 28 : IPVF platform and its characterization facilities

On processing (Figure 29), all major thin film deposition technologies up to 20x20 cm<sup>2</sup>, from solution based (slot die, electrodeposition) to vacuum based process (5 Sputtering, 4 ALD, 3 co-evaporation systems and a MBE, PECVD ...). Also available: laser scribing, annealing furnaces (tubular and RTP).



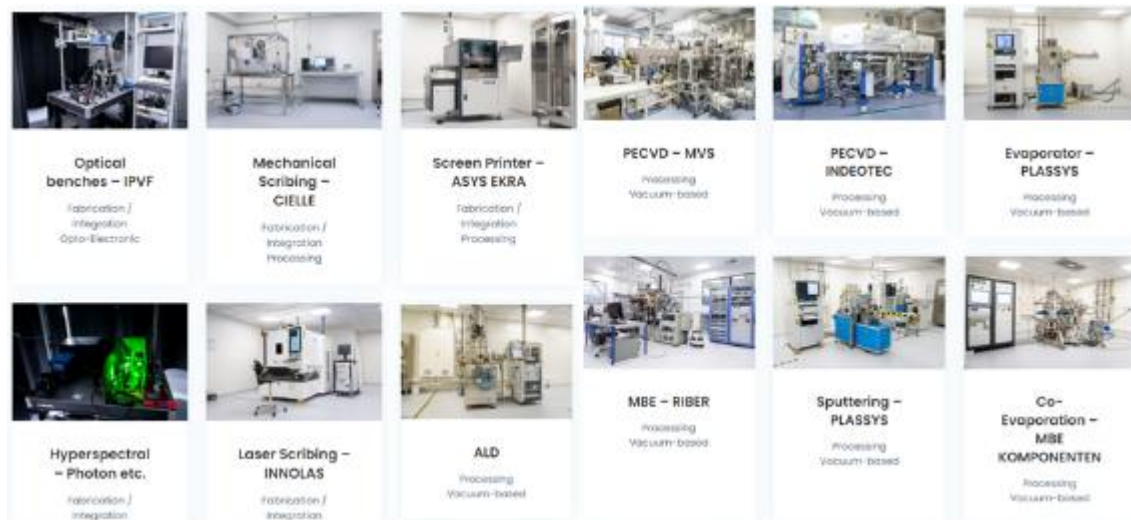


Figure 29 : IPVF processing facilities

## FEDPV

As of January 1, 2022, the CNRS photovoltaic federation comprises 16 laboratories spread throughout France (Figure 30). This group represents nearly 250 people, including more than 130 permanent staff. Other CNRS UMR laboratories, not yet affiliated to FedPV, are in the process of requesting their affiliation to FedPV (LAAS, IMEP-LAHC, etc.).

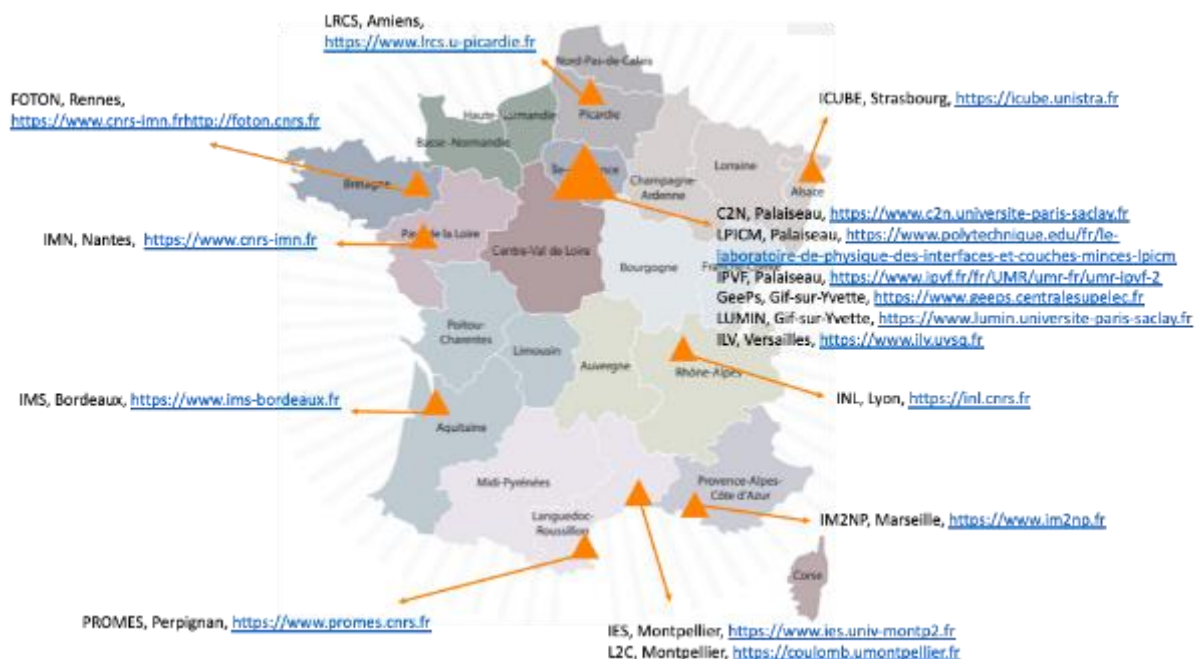


Figure 30 : CNRS photovoltaic federation map

The FedPV laboratories are equipped with characterization tools covering all fields and scales, from nano to macro (Table 3).

Table 3 : main characterization techniques available in the FedPV laboratories, according to the areas of characterizations and scales. The techniques on the yellow background are available in-situ or operando

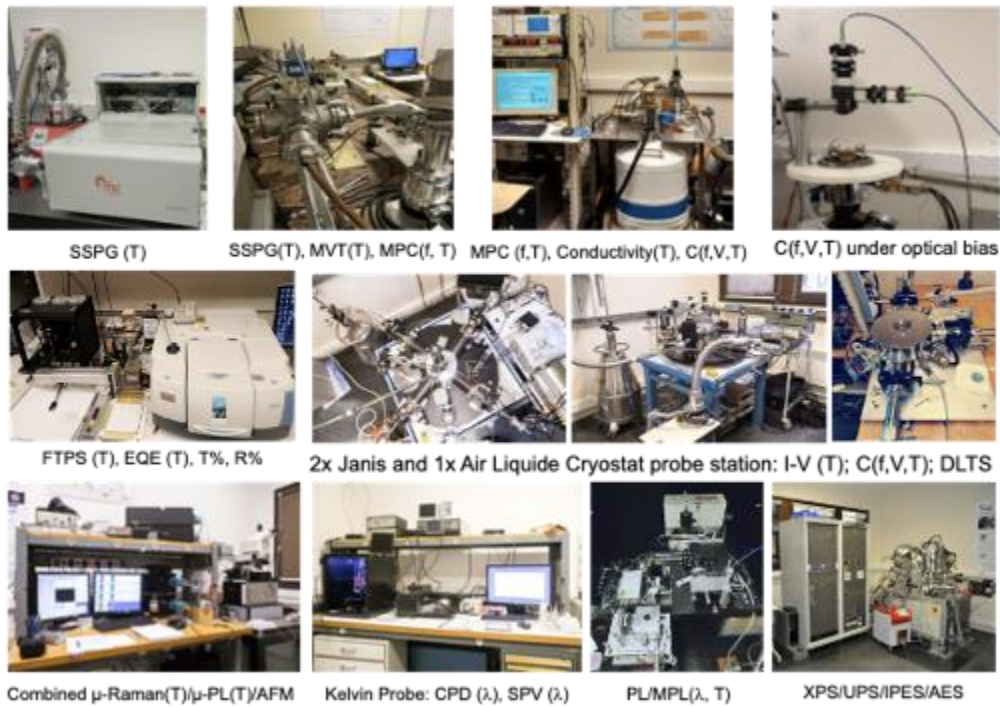
Caractérisation	nm	µm	mm	m	Laboratoires
Chimique	Auger				ILV, GeePs
		XPS, UPS			ILV, GeePs, IMN
	EDS				ILV
	SIMS				GeMAc
			GD-OES		ILV
			ICP, SAA		ILV
			Angle de goutte		ILV, GeePs
Morphologique et structurale	AFM				GeePs, IPVF, IES, ILV
	TEM, STEM				LPICM, LRCS, C2N, IMN
	SEM				LPICM, IPVF, LRCS, C2N, IMN, ILV
		Raman			LPICM, IPVF, GeePs, C2N, IMN
		DRX			LPICM, IPVF, LRCS, C2N, IMN
		Microscopie acoustique			IES
Optique	Ellipsométrie				LPICM, C2N, IMN
		Spectro UV-Vis			C2N, IMN
		FTIR			GeePs, C2N, IMN, IES
Optoélectronique		PL hyperspectrale			IPVF
		TR-FLIM			IPVF, GeePs
		PL, MPL			IPVF, GeePs, LPICM
	CL, TRCL				C2N
		EL			IPVF, GeePs
		TRAS			LRCS
Electrique		I-V cellules et modules			GeePs, C2N, IMN
	C-AFM				GeePs, IPVF, C2N
	KPFM				GeePs, IPVF
	EBIC				C2N
		I-V (T)			GeePs,...
		C(f,V,T) et G(f,V,T)			GeePs, IES
		DLTS			GeePs
		SSPG, SSPC, MPC			GeePs
		FTPS			GeePs, IPVF, C2N
		SPV			GeePs
		PCD			LPICM, GeePs,
		µWPCD			IM2NP
		IMVS/IMPS			LRCS
		I sous onde thermique			IES

## GEEPS

GeePs laboratory (UMR8507) is a joint research unit between CNRS, CentraleSupélec, Paris-Saclay University and Sorbonne University. The electrical characterization of PV materials and devices is one of the major activities of the PV team at GeePs, with approaches ranging from the nanometer to the macro scale. GeePs has a unique AFM analysis facility with homemade electrical extensions; several cryostatic chambers are used to characterize the electrical properties and electrically active defects combining modulated illumination, temperature, time-

dependent applied voltage, with many techniques like admittance spectroscopy, DLTS, Modulated Photocurrent (MPC), Steady-State Photocurrent Grating (SSPG), Fourier-Transform Photocurrent Spectroscopy (FTPS). The laboratory also disposes of instruments for local chemical analysis, structural and strain state analysis, as well as for the analysis of optoelectronic properties by photoluminescence techniques. Finally, GeePs has several outdoor PV metrology platforms where most PV technologies are studied.

#### Characterization platforms: electrical, optoelectronic, structural, physico-chemical properties



#### Outdoor monitoring and measurement platforms





## AFM platforms : Nanoscale electrical characterization

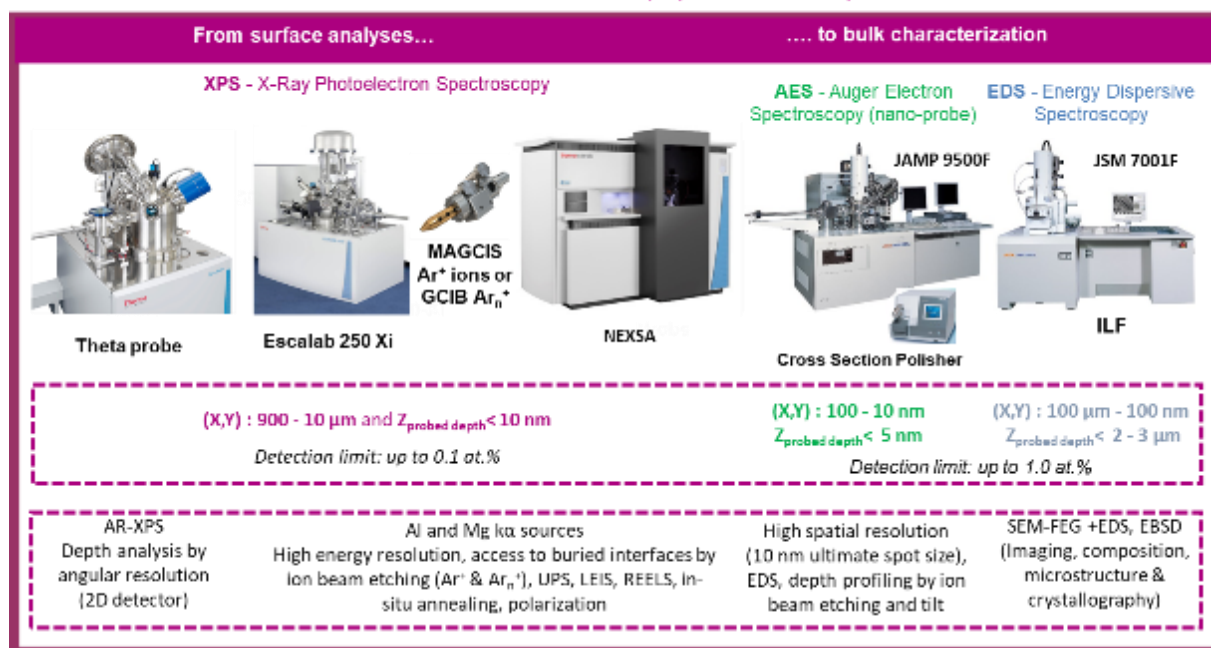


## ILV-CEFS2

This research center hosts a variety of advanced surface characterizations such as angle resolved XPS and Nano-Auger.

**ILV - CEFS2** (Centre d'Etude et de Formation en Spectroscopies électroniques de Surfaces)

### Surfaces and interfaces physico-chemistry



## LRCS (UMR7314)

LRCS Platform (*Figure 31*) mainly offers state-of-art equipment for PV related to in situ / operando characterization techniques based on Electron microscopy and x-ray diffraction for evaluation of materials/interfaces/devices ageing under relevant stressors. In addition, we have the possibility to in depth characterize the dynamic of the different charge transfer processes taking place in PV devices/modules from ms down to fs time resolution, from electrical phenomena (IMVS/PS, EIS, TPV..) to radiative (TCSPC, TRPL) and non-radiative

processes (TRAS). The laboratory is well-equipped for device fabrication under fully controlled atmosphere (DSSC and PSC), characterization of PCE/IPCE and ageing under different conditions in accordance with standard IEC61646/ISOS protocols.

### In situ and/or operando characterization techniques



**Environmental SEM FEI Quanta 200 FEG**  
Micromanipulators (KleinDiek Nanotechnik)  
Microinjection,  
Microindentation,  
Low current measurement  
Air sensitive transfer module  
Temperature and humidity



**HRTEM FEI TECNAI F20-ST 200 keV**  
High speed camera, EELS, EFTEM, HAADF  
Liquid/Electrical/temperature holder  
Poseidon for operando



**HRTEM JEOL 300 keV low dose** for ultra-high resolution and sensitive materials (organic - perovskite)  
Liquid/Electrical/temperature holder  
Poseidon for operando  
Solid/liquid and solid/gas interface  
4D-STEM, 3DED Tomography  
(In lab ready by end 2022)



**X-ray diffraction Bruker D8 Advanced**  
*Reflection and transmission with rotating anodes*  
In situ with and in combination with  
Temperature, humidity, atmosphere,  
electrical bias, light



Semi-automatic screen printer



Ar-filled glovebox for PSC fabrication including spin coaters and two sources with organic thermal evaporator (Mbraun)

### PV processing / ageing



Light soaking chamber for accelerated ageing tests IEC61646



Light soaking chamber for accelerated ageing tests for modules IEC61646



UV laser scribing

Figure 31 : LRCS facilities

## C2N (UMR 9001) CNRS / Université Paris-Saclay

The Centre for Nanosciences and Nanotechnology (C2N) is a joint research unit between the CNRS and Université Paris-Saclay. It was founded on the 1<sup>st</sup> June 2016 by merging two former

laboratories, the Laboratoire de Photonique et de Nanostructures and the Institut d'Electronique Fondamentale and at present it counts 410 people (<https://www.c2n.universite-paris-saclay.fr/en/>).

The center develops research in the field of material science, nanophotonics, nanoelectronics, nanobiotechnologies and microsystems, as well as in nanotechnologies. In all these fields, its research activities cover all the range from fundamental to applied science. The laboratory is organized around four scientific departments.



**RENATECH** technology centers include **C2N**, **LAAS**, **FEMTO ST** (<https://www.renatech.org/en/nos-implantations/>), 7300 m<sup>2</sup> of clean rooms, 150 engineers et technicians, 130 M€ of equipment overall.

#### 12.1.3 SHS @ CNRS-Universities joint research units (UMR)

Higher Education system (Universities and Engineering schools) and CNRS cover all the fields of knowledge in Humanities and social sciences, including Sociology, Economy, Law, History, Geography, Urbanism ... As per CNRS only see <https://www.inshs.cnrs.fr/fr/institut>

Labs that are active in the fields covered by TASE are over 30, and include PACTE and CIRED, as large entities, and many other smaller groups.

#### 12.1.4 Environment@ CNRS-Universities joint research units (UMR)

Higher Education system (Universities and Engineering schools) and CNRS cover all the fields of knowledge in environmental sciences. In CNRS alone, topics of TASE are covered in 2 Institutes: INEE (<https://www.inee.cnrs.fr/fr/institut>) and INSU (<https://www.insu.cnrs.fr/fr/institut-national-des-sciences-de-lunivers>). Labs that are active in the fields covered by TASE are over 40, and include LMD, MNHM, G-SCOP and RASSODEE, as large entities, and many other smaller groups.

Regarding PV topics, CNRS and CEA are recognized as world-class RTO (*Figure 32*).

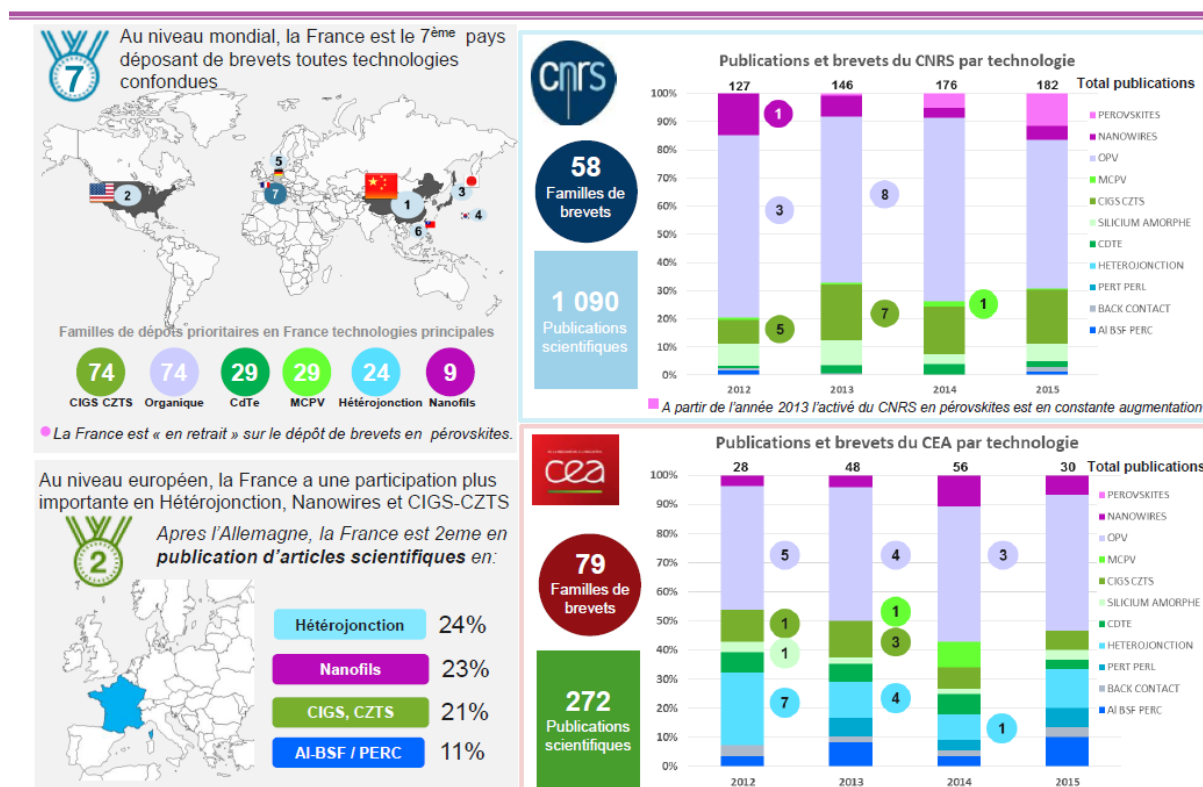


Figure 32 : Both CEA and CNRS are world class innovators in photovoltaic technologies (source: ANCRE CVT<sup>114</sup>).

## 12.2 ANNEX 2: CEA SKILLS in TASE

### 12.2.1 CEA expertise on networks

To meet the challenges of the energy transition and the objective of carbon neutrality by 2050, to cope with the efficient integration of renewable energies into the energy mix and the development of new uses, energy networks (heat, electricity, gas) must be rethought. From their architecture to their management, from components to systems, the CEA teams are working to design smarter, more resilient, more efficient and more economical networks.

### Developing networks to decarbonize energy

At present, energy transport and distribution networks (electricity, gas and heat) are mainly designed based on unidirectional and centralized production, transport and distribution models. The increase in the share of renewable energies in the energy mix, which are intermittent by nature, and the development of new uses (electric cars, massive production of hydrogen via electrolysis, self-consumption, etc.), mean that these networks need to evolve. The challenge is to introduce flexibility into the energy system in order to manage the variability of supply and demand at a controlled cost, both in time (intermittency, seasonal variations in consumption) and in space (differentiated local uses), by using the most suitable storage and/or conversion systems. The objective is to improve energy efficiency by distributing energy as accurately and reliably as possible, in real time, in a centralized and decentralized manner and at a competitive cost.

### How will the networks evolve?

<sup>114</sup> <https://www.allianceenergie.fr/cvt-ancr-publie-etude-potentiel-technologique-economique-filieres-pv-a-haut-rendement/>

In the very short term, the aim is to improve network management by better taking into account and adjusting the demand of both private individuals and industry. To do this, networks must be more connected and "intelligent", so that the operator can have continuous access to a maximum amount of information in a secure manner to know how to balance his network at any time and on any scale. These "smart grids" technologies rely on a multitude of sensors to monitor the system, software capable of processing this mass of data to extract the necessary information, and real-time decision support tools. They enable the various producers, consumers and storage facilities to be controlled in a coordinated manner.

The time will then come to interconnect these different energy networks, particularly at local level, to further increase the flexibility of the system. The aim is to take advantage of the synergies between energy carriers.

The third stage will correspond to the massive arrival of electric vehicles, the appearance of new uses of electricity and the transfer of part of the electricity production to other energy carriers (heat, gas). The new uses, which lead to an increase in electricity consumption, offer new possibilities for managing the flexibility of the networks as long as the energy system is managed in a global approach.

### **Energy network management at CEA**

The CEA has extensive expertise in the field of energy network management.

This area is divided into two themes, the first of which is the development of software and components essential for the real-time management of an energy network, whether it transports electricity, gases or heat, and the second is the development of all the flexibility solutions essential for its management, such as storage systems, the hydrogen vector and converters between vectors.

### **Components and digital technology for smart energy grids**

Research efforts must be intensified on digital technologies for intelligent management of the energy system:

- from data acquisition (with specific sensors),
- the transmission of information to a centralized or on-board system,
- initial processing to identify reliable data,
- then more complex processing to qualify the state of the networks
- and, above all, to anticipate production and consumption in order to be able to arbitrate between different strategies.

This requires converters that can operate at high frequency, are compact, highly efficient and low cost. This type of component is being developed at the CEA in collaboration with the G2Elab and the NEEL Institute, internationally renowned laboratories on these subjects. Specific converters for connecting solar modules to the electrical grid will also be developed to improve the conversion efficiency in current voltage ranges that have not been developed to date (MVDC target).

Concerning modelling and simulation, the CEA is working on the development of a sizing tool for multi-vector networks combining electricity, heat and gas. This tool, based on the co-simulation resources developed at the CEA (*Figure 33*), brings together the various models of energy components being developed in the CEA laboratories. The models will be interoperable and should enable the simulation of the operation of complex energy systems, combining different production sources (nuclear, photovoltaic, wind, STEP, etc.), different uses and



storage solutions. This sizing can be carried out under multiple constraints: economic, use satisfaction, etc.

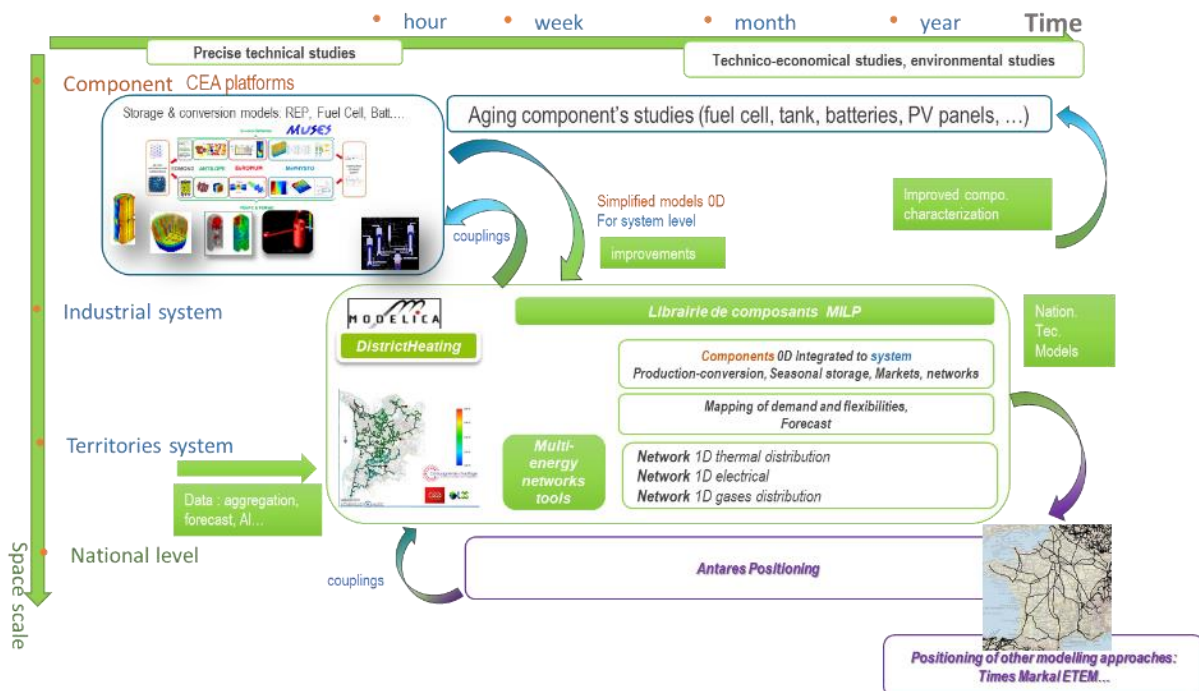


Figure 33 : CEA co-simulation platform developments

## Connections between Energy networks

In the CEA's vision of an integrated energy system, the physical connection between the various energy networks is fundamental, as it provides the flexibility. The aim here is to develop specific components and modelling tools to simulate their operation in interconnected local loop networks. Research and development focuses in particular on energy systems for connecting the electrical network and the heat/cold network, always seeking solutions adapted to the context of use and optimizing the conversion efficiency. In this context, the close links with LEGI will be a real asset.

As stated in the PPE, the decarbonisation of energy systems must be done simultaneously with the improvement of energy performance and lead to a more efficient overall energy balance.

This axis is articulated in 3 sub-axes:

- Reduction of energy losses and reuse of waste energy (e.g. waste heat) – *partially included in PEPR ("industry decarbonisation")*
- Saving energy and materials during the life of a product
- *Circular Economy of Carbon (addressed in other PEPR) – not detailed hereinafter.*

## Reduction of energy losses and reuse of waste energy

The reduction of energy losses is a crucial issue to limit energy consumption despite the increase in population and needs. Two sectors offer significant potential savings, particularly in France: transport and buildings. The CEA is focusing its research on the development of



materials and technologies to reduce the energy consumption of vehicles and homes. Research focuses, for example, on lightening materials or on material solutions associated with solarized buildings, integrated into a broader energy system. This approach complements those of the INEF4 and “Efficacity” institutes and the CSTB.

### **Saving energy and materials during the life of a product**

To anchor its position in the energy and environmental transition, the CEA aims to develop technologies with a low environmental footprint; a footprint that includes greenhouse gas emissions, energy consumption, the use of critical/toxic materials, or the emission of toxic effluents, throughout the product life cycle. Life cycle assessment (LCA) tools are used for this purpose and the methodology is widely deployed in CEA laboratories. An LCA organization is now in place with relays in each department and between the different operational departments.

For the various technologies developed at the CEA, the grey energy (i.e. the energy required to manufacture the product) is estimated as well as the greenhouse gas emissions produced during the manufacture of the product.

Many components essential to the energy transition call on materials classified as critical by the European Commission: rare earths (neodymium and dysprosium for magnets), platinum for fuel cells, gallium (thin-film PV) as examples. In view of this, the CEA is working on substitution elements (e.g. replacement of TCO for PV cells) when possible, or positioning critical elements in components so that they provide the same functions in reduced quantities. The search for optimized architecture is integrated into the deployment of a network of experts around the concept of "materials by design" at the CEA.

The CEA is working on recycling processes for PV cells and modules (European project Cabriss coordinated by the CEA) and on component dismantling techniques. More generally, the principle of eco-design, which integrates environmental constraints from the design stage and provides for easier recycling of the product at the end of its life, will be widely deployed, following the example of the first studies carried out on photovoltaic modules.

## **Developing smart, more interconnected, more efficient and more sober networks**

### **Digital technology and IA to model, simulate, optimize and control complex systems**

In order to control energy networks efficiently and economically, the CEA is developing simulation tools to design, size, control and optimize these complex networks combining different means of production, conversion, storage and use. It is also developing artificial intelligence (AI) systems capable of assisting decision-making.

The accurate anticipation of consumption and production makes it possible to improve the efficiency of the entire system. However, a bias always exists between anticipation and real time. The CEA is therefore developing algorithms for optimizing operation, information systems providing communication interfaces and data management to be able to diagnose and evaluate network performance in real time. These developments are framed by economic models for the sale of energy to predict and decide, in real time, on the most efficient, most sober and least expensive energy solution.

For example, the CEA has developed a tool to assist in the management of heating networks, making it possible to anticipate needs based on meteorological data and to distribute heat as accurately as possible to the various delivery points in the network, resulting in a gain of around 7% in annual energy savings.

Platforms and demonstrators enable "life-size" tests to be carried out on the scale of a house, a building, a district or even a territory, as on the CEA-Liten "smart grid" systems platform, located in Chambéry. Different network configurations are thus tested with different storage resources via a simulator, to define the most efficient control strategies and optimize profitability.

## Testing network configurations and control

### A platform for testing complex energy systems

The aim is to test energy management solutions on complex networks (electricity, gas, heat) in real conditions before their deployment. This is the case, in particular, of the "Plateforme d'Intégration de Systèmes Energétiques" (PISE) in Chambéry and its planned Smart Cad extension in Cadarache. PISE is a platform in a semi-virtual environment, i.e. aimed at testing real components on real networks, but whose uses are simulated (virtualized). This makes it possible to create various usage profiles and to identify their impact on the overall functioning of the system. The Cadarache extension project will aim to monitor the actual usage of around 5,000 consumers, with more than 200 electric vehicles available and 125 charging points.

The Smart Grid platform (*Figure 34*) is dedicated to the analysis of the integration of renewable energies into electrical networks at different scales (from micro island networks to large continental networks).

It includes (*Figure 35*):

- an area for characterizing electrochemical storage technologies, from the single cell to the battery pack, with a capacity of over 300 test channels up to 250 kW and 40 climatic chambers,
- an abuse test area for battery cells, allowing tests on overloads, short circuits and thermal runaway,
- an experimental low-voltage power distribution microgrid (PRISMES) with a power rating of around 200 kVA, including real or simulated production-consumption means, photovoltaic field and battery pack simulators, unstable static converters, deforming loads, a generator plant, recharging stations for electric vehicles, etc,
- a power electronics area comprising 6 test chambers dedicated to the development, fine-tuning and testing of innovative static converters, including high-voltage converters, up to powers of around 250 kW,
- 10,000 m<sup>2</sup> of outdoor area (roof and open field) equipped with conventional photovoltaic fields as well as an area of PV fields operating at high voltage DC (3000 V DC)
- a set of digital tools including a SCADA, simulation and calculation means, a digital safe for storing our local or remote monitoring data.

### Territorial demonstrators: the example of the TOTEM platform

Various territorial demonstrators have been set up in collaboration with the CEA teams. The

thanks to its energy production and control system. Its operation is based on the activity of infrastructures (batteries, hydrogen, etc.) and on photovoltaic production. In order to adopt a more sober approach to energy consumption, the teams will also be able to control the energy management of the building thanks to the development of the Energy Management System (EMS), a control tool developed by the CEA and implemented on TOTEM.

### **A concrete example of a smart network**

The CEA is a stakeholder in an advanced management project, launched in 2014, for the heating networks of the cities of Metz and Grenoble, in collaboration with the operators of both cities (UEM in Metz and CCIAG in Grenoble). A heating network management tool, DistrictLab-H, has thus been set up to better manage production. This simulation tool uses advanced mathematical methods for modelling, but also a self-learning system based on artificial intelligence to manage user requests in advance. This allows for dynamic, real-time management of networks. DistrictLab-H was deployed in 2021 in both cities and is currently in use.

## **12.2.2 CEA expertise on photovoltaics**

### **Photovoltaic generation**

The CEA has historically worked on silicon technologies and in particular on heterojunction technology to target high efficiency. For several years now, the CEA has also been conducting research on perovskite materials and their integration into functional stacks. The development of multi-cation materials is at the heart of the scientific issues raised. Given the promising nature of the initial results, the work is now being extended to the problem of understanding the role of interfaces in the functioning of cells, the formulation of P and N layers, and the study and understanding of ageing phenomena in relation to encapsulation materials. Initial promising results have been obtained with high yields (>15%) on large surfaces (50\*50 mm<sup>2</sup>). The long-term objective is to integrate this type of cell with a silicon cell in so-called "tandem" structures in order to aim for efficiencies of over 30%.

### **Integration of photovoltaics into the energy mix**

The decrease in module costs favors the integration of PV cells for a wide range of applications. The activities of the CEA's building and electrical networks departments, based on the platforms of the INES campus (INCAS, Fact and PRISME), focus on the integration of photovoltaics in a global vision. It includes not only the physical integration of multifunctional modules but also the development of concepts that make the building an energy node capable of evolving towards high rates of self-consumption while integrating into the neighborhood or "city of the future". In this vision, the building is seen as an energy consumer and producer, capable of exchanging energy flows with its neighbors. The use of solar sources is the only way to develop zero energy or even positive energy buildings.

This activity around the integration of photovoltaics at controlled costs and allowing the maximum production of MWh from a producible is at the origin of the ITE ("Institut de Transition Energétique") INES-2S (*integrated solar solutions*) whose financing was validated in May 2019 for a period of 5 years.

### **The solar PV platform at CEA**



The platform consists of:

- a “materials” platform comprising laboratory, pilot (60 kg) and industrial (1200 kg) scale technical resources dedicated to the crystallization of silicon ingots, industrial equipment for cutting into bricks and wafers, and equipment for characterizing chemical, crystallographic, structural, mechanical and optoelectronic properties,
- the RESTAURE class 100 000 clean room of 1300 m<sup>2</sup> (*Figure 36*), containing the equipment needed to optimize and carry out the various stages of the PV cell technologies developed on the wide variety of silicon substrates that can be considered, including those developed at the CEA. A 300 m<sup>2</sup> extension to the room has recently been completed to integrate the activity on innovative Si/perovskite tandem and Si TOPCon cells. The platform includes pilot equipment for demonstrators and industrial equipment,
- the “LabFab-HET” pilot line on which the developments of the heterojunction photovoltaic cell technology are carried out. The surface area of the clean room is 1500 m<sup>2</sup> and the batch sizes are several thousand cells per day thanks to robotisation, equipment and industrial-type processes, the objective being to carry out the development and proof of concept of this technology on an industrial scale in order to be able to transfer it to our partners,
- a “R&D module” platform (*Figure 37*) comprising equipment for the manufacture, characterization and accelerated ageing of photovoltaic modules. The equipment present allows the production of customized modules on standard or very specific technologies, as varied as light or integrated modules for buildings, roads, vehicles or space. The platform is versatile and can address both low TRL upstream projects and projects that can lead to demonstrators in terms of quantity of notable modules and technology transfer. The test and characterization facilities enable the characterization of the materials and the modules produced, in environments or climates adapted to the needs of the partners (thermal cycling, freezing humidity, UV, outdoor bench, etc.). The platform also relies on the resources of the “Durasol” infrastructure (<https://www.durasol.fr/>).
- the equipment necessary for the development of organic cells (OPV) on rigid or flexible substrates and their encapsulation by industrializable techniques such as inkjet printing or roll-to-roll coating.

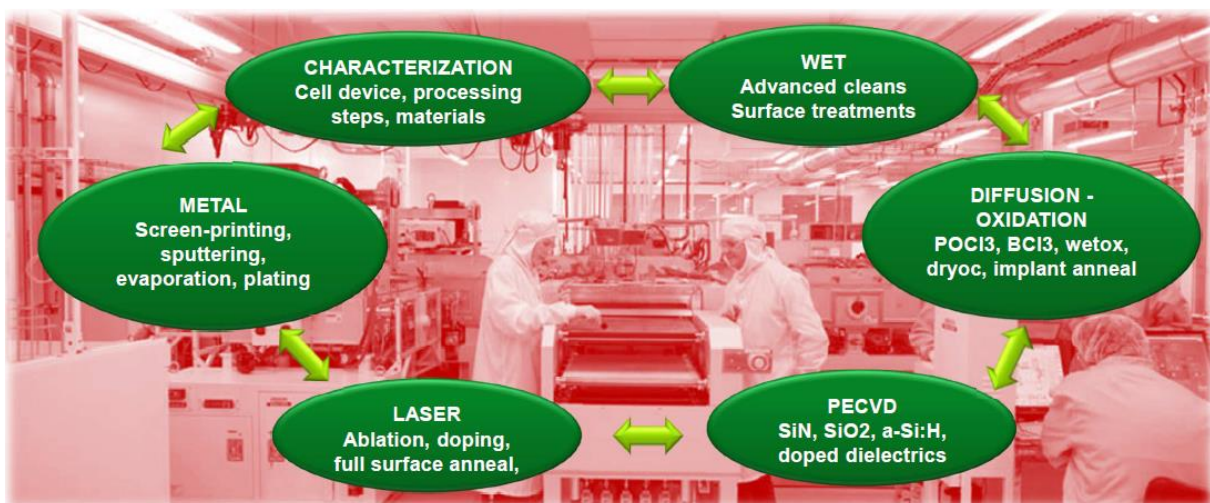
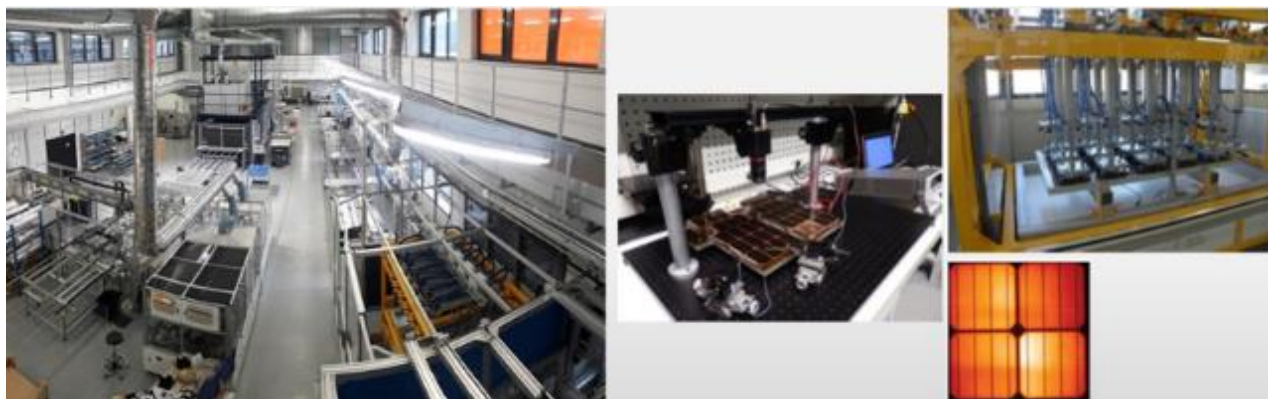


Figure 36 : « RESTAURE » clean room at CEA



*Figure 37 : « R&D Module » platform at CEA*



## 12.3 ANNEX 3: DETAILED DESCRIPTION of the TARGETED PROJECTS

## 12.3.1 TP 1: HyMES - Hybrid modelling for Multi Energy Systems

Project title	
<b>TP 1: HyMES - Hybrid modelling for Multi Energy Systems</b>	
Year of Launch	Budget allocation
T0	1.89 M€

## 12.3.2 TP 2: DC-Architect - Co-designing the future of MV distribution grids with their power electronics components

Project title	
<b>TP 2 DC-Architect - Co-designing the future of MV distribution grids with their power electronics components</b>	
Year of Launch	Budget allocation
T0	6.06 M€

## 12.3.3 TP 3: AI-NRGY - Distributed AI-based architecture of future energy systems integrating very large amounts of distributed sources

Project title	
<b>TP 3 AI-NRGY - Distributed AI-based architecture of future energy systems integrating very large amounts of distributed sources.</b>	
Year of Launch	Budget allocation
T0	1.89 M€

## 12.3.4 TP 4: IOTA- Innovative thin-films/silicon tandem architectures

Project title	
<b>TP 4: IOTA - Innovative thin-films/silicon tandem architectures</b>	
Year of Launch	Budget allocation
T0	5.76 M€

## 12.3.5 TP 5: Smart4Module - Smarter and Eco Innovation building blocks for advanced PV Module

Project title	
<b>TP 5: Smart4Module - Smarter and Eco Innovation building blocks for advanced PV Module</b>	
Year of Launch	Budget allocation
T0	3.39 M€

## 12.4 ANNEX 4: TOPICS of the CALLS for PROPOSALS (CP)

## 12.4.1 CP 1: Environmental impacts of energy systems

Proposed title for the “call for proposals”
CP 1: Environmental impacts of energy systems

Year of Launch	Budget allocation
T0+3 Months	4.67 M€

Context presentation
<p>« Energy transition » is the transformation of the existing fossil fuels-based energy system to reduce the environmental impact of the production, distribution and consumption of energy (electricity, gas, etc.). This transition creates new environmental impacts among which land use and habitat loss, fossil resources and water use, and the use or dissemination of hazardous materials during the industrial processes of production and transport. The types of impacts vary greatly depending on the scale of the system, technologies, the countries involved in the value chain from the extraction of resources to the installation of the finished products making the infrastructure. They also vary in time with the improvement of industrial processes material contents and technologies.</p> <p>The life-cycle assessment (LCA) is one approach to examine the environmental impacts of an energy system throughout its life cycle, from the production of raw materials to its recycling. It is a modelling tool based on internationally accepted standards<sup>115,116</sup> and comes in support to decision making.</p> <p>Performing LCA needs a large amount of data. If the input data are poorly constrained, incomplete or flawed, the analysis will not lead to solid conclusions. There is thus a <b>need to develop dedicated databases with well-documented metadata</b>.</p> <p>LCA also feeds the technical and social debate about the expansion of renewables in the energy mix. For the last decade, IPCC has reviewed the « carbon performance indicator », which is a proxy of the carbon footprint of energy supply systems. It revealed the extent of the distribution of the results for each of energy supply system, reflecting the great variability of local conditions and technological characteristics of systems in the available studies. It would therefore be fruitless to attempt identifying the contribution of each energy supply system with a unique value of carbon performance, which lead to a partial view of the problem. Instead, a <b>better consideration of local specificities is needed</b>. Moreover, the carbon footprint is one indicator among others. It <b>does not address other environmental impacts, such as wildlife impacts, land surface impacts, depletion of natural resources or human health</b>. To contribute to the debate on energy transition, these environmental assessments must be conducted properly i.e. by taking into account technological and local specificities.</p> <p>Finally, in the context of the climate urgency, innovation and regulation are evolving at fast pace with strong implication on energy systems (i.e. energy mix). The assessment of the environmental</p>

<sup>115</sup> International Standard Organization (ISO). Environmental management - Life cycle assessment: Principles and framework. ISO14040. (2006).

<sup>116</sup> International Standard Organization (ISO). Environmental management - Life cycle assessment: Requirements and Guidelines. ISO14044. (2006).

impacts of the energy system thus **requires a dynamic (including the improvement of technologies) and systemic (including coupled industrial processes or conditions of use) modelling, which is generally lacking in standard LCA.** Dynamic modelling also allows including new **usage/applications of renewable energy systems that may lead to positive impacts while mitigating negative ones** (e.g. agrivoltaics...). It also provides aggregated proxys that can be used to compare the impacts of different scenarios of implementation at both the global, national and regional levels as well as the couplings with the existing infrastructure. This is a key point to define the best territorial integration.

### Positioning with respect to the state of the art

The environmental impacts of various systems of production and consumption have been studied for several decades by developing and applying life cycle assessment (LCA) with its own ISO standard. LCA studies depend on data of uneven quality and quantity<sup>117</sup>, assumptions and scenarios, as LCA assesses the real world in a simplified model. Assumptions and scenarios may vary from one study to the other, leading to different LCA results<sup>118</sup>. These variations in LCA approaches and results may be confusing, especially for non-experts so that, education and training is required to assist users in the application of LCA<sup>119</sup>. Going-from globally to regionally assessed environmental impacts is key to facilitate decision-making. The concept of regional LCA has emerged a decade ago<sup>120</sup> and based on only few recent LCA studies<sup>121</sup>, a sustainable energy development plan can be designed at regional scale. This approach needs to be further developed and expanded in order to address its dynamic (evolution with time) and systemic approach (from one technology to energy mix). In addition, LCA should not be misunderstood as a comprehensive or a complete assessment. The assessment of social sustainability, and its integration with economic and environmental sustainability, are still in the developmental stage and recent developments were initiated to broaden traditional environmental LCA to a more comprehensive Life Cycle Sustainability Analysis (LCSA). Further developments need to be conducted to integrate LCA with non-accounted environmental, societal (i.e. societal life cycle assessment SLCA<sup>122</sup>) and economic impacts, and promote the use of LCSA for the cohesive achievement of the United Nations (UN) Sustainable Development Goals (SDGs) framework. Finally, new usage of energy systems have shown potential to minimize negative environmental impacts while maximizing positive environmental impacts. For instance, agrivoltaics (or agrophotovoltaics) have been developing as a way to simultaneously produce energy, reduce evaporation (through shadowing) and maximize crop yield and quality<sup>123,124</sup>. However, the benefit versus cost of agrovoltaics is difficult to assess, as it depends on the crop type, local hydrological cycle, solar radiation

<sup>117</sup> Guo M., Murphy R.J., 2012 : LCA data quality: Sensitivity and uncertainty analysis, *Science of The Total Environment*, 435-436, 230-243, doi:10.1016/j.scitotenv.2012.07.006.

<sup>118</sup> Qin Y., 2019 : Characterizing uncertainties in life cycle assessment. *UC Santa Barbara*. PhD dissertation. 123 pp., <https://escholarship.org/uc/item/99m421b1>

<sup>119</sup> Maastricht University organizes an online LCA course: "Life Cycle Assessment: Basic Principles and Uses", <http://www.um-lca-course.nl>, developed and implemented within the framework of Chemelot InSciTe, with support of the Province of Limburg, the Netherlands

<sup>120</sup> Wegener Sleeswijk A., 2011 : Regional LCA in a global perspective. A basis for spatially differentiated environmental life cycle assessment. *Int J Life Cycle Assess*, 16, 106–112, doi:10.1007/s11367-010-0247-5

<sup>121</sup> Tabatabaie S.M.H. et al., 2018 : A regional life cycle assessment and economic analysis of camelina biodiesel production in the Pacific Northwestern US. *Journal of Cleaner Production*, 172, 2389-2400, doi:10.1016/j.jclepro.2017.11.172.

<sup>122</sup> Hunkeler D., 2006 : Societal LCA methodology and case study. *Int J Life Cycle Assessment*, 6, 371-382

<sup>123</sup> Dinesh H. and Pearce J.M., 2016 : *The potential of agrivoltaic systems. Renewable and Sustainable Energy Reviews*, 54, 299–308.

<sup>124</sup> Valle B. et al., 2017 : Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Applied Energy*, 206, 1495-1507, doi:10.1016/j.apenergy.2017.09.113.

availability, so dedicated research is still needed<sup>125</sup>. Also new usage/applications of energy system (technology mix...) may be imagined to minimize the detrimental impacts on the environment and maximize the benefits.

### Detailed topics

Two type of projects are welcome: projects addressing life cycle analysis and environmental impacts on the one hand and projects addressing new usage and applications for improved environmental impacts on the other hand. The following challenges that are relevant for one of the project types should be addressed :

- **Developing dedicated database for environmental impact assessment**, including documented metadata: the call will support project developing well-documented, high quality and regional data are needed. In the perspective to expand environmental and socio-economic impacts in the frame of LCSA, the projects should envisage adding economic and social inventories and indicators to the environmental framework. In addition, assessment experts may have difficulties in judging the data selection if they are not experts in all subjects of the study. Therefore, interdisciplinary collaboration between assessment experts and researchers from other expertise domains is sought.
- **Assessing LCA uncertainty**: the call will support projects that identify uncertainty sources in the LCA process, determine how uncertainty propagates, propose a methodology to model, and quantify the uncertainty associated with LCA.
- **Improving environmental impact assessment modelling in LCA**: Although LCA is standardized, its adaptation to each type of system producing electrical energy remains delicate and requires fundamental research in order to remove a number of scientific barriers. Regionalized, dynamical and systemic modelling of environmental impacts, including multi-physics and multi-scale modelling, needs to be developed to narrow distribution of LCA or LCSA, enhance its relevance to support decision-making at local scale and include its possible evolution at various time horizons for prospective purpose. The call should address:
  - the definition of the boundaries of the system and the concept of Functional Unit adapted to each of the chosen uses.
  - the assessment of the impact of the lifetimes of the technological system on performance in terms of sustainable development. This involves taking into account the aging of systems through analyses to estimate potential failures that impact the true life of the system.
  - the development, beyond the traditional application of LCA as a product-oriented methodology, a new regional LCA-based approach to assess geographically or administratively defined systems.
  - the assessment of the consistency of the databases needed to perform an LCA and their influence on the final results through statistical sensitivity analysis.
- **Expanding to non-accounted environmental and socio-economic impacts, from LCA to LCSA :**

<sup>125</sup> Toledo C., Scognamiglio A., 2021: Agrivoltaic systems design and assessment: a critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns). Sustainability, 13, 6871, doi:10.3390/su13126871

- Integrating environmental and ecosystem impact in LCA to assess the impact of the implementation of an energy system directly in the ecosystem and environment and the modification that will occur. There is therefore a need for the addition of new criteria and metrics describing the impacts of technological systems on the user and/or the ecosystem neglected until now by the LCA standardized method.
- Encouraging the integration of LCA with other advanced modelling techniques to better incorporate social, environmental, and economic considerations for improved LCSA methodology together with societal LCA (SLCA). Human well-being is a central concept to be defined and articulated in order to integrate societal aspect in LCA and LCSA to promote the improvement of social conditions throughout the life cycle of a product.
- Linking Life Cycle Sustainability Assessment (LCSA) and Societal Life Cycle Assessment (SLCA) with the Sustainable Development Goals (SDGs) : the projects should explore how LCSA can contribute to the achievement of the SDG framework as a whole and further develop the assessment and coverage of interlinkages, trade-offs and prioritization of SDGs in LCSA and SLCA methodologies. They should evaluate by impact indicators defined upstream of the services provided by energy system to the corresponding SDGs (fight against global warming, territorial resilience -compass-, local economic benefits for citizens, create jobs, create pedagogy, etc.), and evaluate by a multi-criteria decision support analysis (SWOT or MCDA type) the sectors via these SDGs and LCA, SLCA, LCSA.
- **Exploring new usage/applications of renewable energy systems for optimizing environmental impacts:** New usage/applications of energy systems can be part of nexus (e.g. water-energy-food) that can help minimizing detrimental impacts on the environment while maximizing positive externalities. One example that deserve attention in this call is agrivoltaics. Research still needs to be conducted to assess the negative and positive externalities of agrovoltatics, and identify potential synergies and minimize trade-offs between renewable energy and other ecosystem services. In addition, a careful evaluation of the potential of electrical system coupled with heating systems or with vehicle to grid or to home for environmental improvements is desirable. The call will also welcome new usage and application of energy systems with similar objectives.

Proposals need not address all the topics of the call. However, if some important topics were missing, some of the available funding would be reserved for a second call for proposals targeting the missing topics.

### Expected results

The expected results of the call is to build database suited for environmental impact assessment of energy systems (PV, wind energy) if possible integrated in existing environmental data hubs, improve environmental impact assessment modelling for energy systems and identify high-potential innovation in energy system usage/application to minimize detrimental impacts on the environment and maximize the benefits.

**List of key words**

Energy systems ; Photovoltaics ; Wind energy ; Agrovoltatics ; Electrical mobility; Environmental impact assessment

### 12.4.2 CP 2: Efficient and flexible energy management of systems under massive share of renewables

**Proposed title for the “call for proposals”**

**CP 2: Efficient and flexible energy management of systems under massive share of renewables**

Year of Launch	Budget allocation
T0+3 Months	5.05 M€

**Context presentation**

Distributed renewable energy sources are reaching significant shares while new energy uses are emerging. These changes are bringing new challenges for energy management due to high proliferation and variability of distributed energy resources and increasing pressure on the distribution networks. The aim of this call for proposals is development of new methods for better understanding, design and management of energy networks on the local level, going from a neighborhood or an industrial complex to the distribution grid. In order to achieve this goal it is important to have more accurate generation and demand prediction on the fine grain level and to enable all sources of flexibility, including taking into account the interactions between different energy vectors and usage (electricity, heating, cooling, renewable gas, e-transport), and the connection to the energy transport network.

**Positioning with respect to the state of the art**

Renewable energy generation and related variability issues have been in the center of the academic research for several decades<sup>126,127,128,129</sup>. However, most of the existing research considers one particular aspect in isolation, without taking into account the feedback of the local decisions on the overall system. This was a reasonable assumption in early days of renewable generation, but with massive share of renewables and proliferation of new usage this is no longer enough. In order to be able to accommodate massive renewable generation, there is need for new research projects that take into account the interplay of different energy vectors and usage, different distributed energy prediction and control methods, and their impact on the distribution and transport network, in particular in terms of energy storage and flexibility management to guarantee the system stability<sup>130</sup>. Flexibility management has mainly concentrated on power control at a certain point in time. New flexibility management methods and markets should be

<sup>126</sup> M. Bollen, F. Hassan. Integration of Distributed Generation in the Power System. Wiley Online Library. 2011. DOI:10.1002/9781118029039

<sup>127</sup> D. S. Callaway and I. A. Hiskens, "Achieving Controllability of Electric Loads," in Proceedings of the IEEE, vol. 99, no. 1, pp. 184-199, Jan. 2011, doi: 10.1109/JPROC.2010.2081652.

<sup>128</sup> G. Kariniotakis. Renewable Energy Forecasting: From Models to Applications. Elsevier. 2017.

<sup>129</sup> D. K. Molzahn, F. Dörfler, H. Sandberg, S. H Low, S. Chakrabarti, R. Baldick, J. Lavaei. A survey of distributed optimization and control algorithms for electric power systems. IEEE Transactions on Smart Grid, 2017.

<sup>130</sup> M. Chertkov and G. Andersson, "Multienergy Systems," in Proceedings of the IEEE, vol. 108, no. 9, pp. 1387-1391, Sept. 2020, doi: 10.1109/JPROC.2020.3015320.



developed that fully take into account the nature of the flexible resources, their quality of service requirements, and their energy and ramping capacity<sup>131</sup>.

#### Detailed topics

- 1- Local energy production and demand forecast:** developing new methods adapted to the energy management on the finer geographical/temporal scales with higher accuracy and taking into account various sources of data, e.g. combining weather forecasts and local measurements. Impact of massive energy and flexibility management on the accuracy of the existing and new prediction methods. Different energy usage and energy vectors should be considered.
- 2- New management/control methods of flexibility sources and services** (on local, but also distribution or transport network level). Design and operation of multi-temporal (from some seconds to some days) and multiscale energy storage systems. Flexibility through the management of multi-energy systems. New flexibility management methods that can accommodate large amount of different flexibility sources and their energy vectors. New methods and pricing mechanisms, flexibility market extension of clearing mechanisms with non-linear market models. Assessing the impact of the imperfect/strategic information on market equilibria and flexibility service providers.
- 3- Energy management methods for local communities** in the broad sense (neighborhood, city district, industrial zone, island micro-grid...) and under various objectives (self-consumption models, maximization of the share of renewable generation, mutualisation of investment ...).
- 4- Inter-community energy management.** Coordination of local communities (with potentially different objectives) and with other actors (including distributed generation and usage, industry, prosumers, aggregators, network level flexibility services...) and including connection between the energy distribution and transport networks. Management of distributed energy systems.

Proposals need not address all the topics of the call. However, if some important topics were missing, some of the available funding would be reserved for a second call for proposals targeting the missing topics.

#### Expected results

- New prediction and energy management methods that enable integration of all flexibility sources on the distribution network level and counterbalance the variability and intermittence of renewable generation.
- The proposals should propose key performance indicators and define reference use cases.
- The proposals should integrate a multidisciplinary approach.
- The proposals should address the validation of their proposed methods (in real, semi-virtual or virtual environment) and include a benchmark.
- The data used for the validation should be delivered in open source.
- The proposal should address TRL 1 to 4.
- The proposals should address multi-stakeholders energy projects involving multi-criteria decision analysis.

<sup>131</sup> S. Meyn, T. Samad, I. Hiskens, J. Stoustrup. Energy Markets and Responsive Grids: Modeling, Control, and Optimization. The IMA Volumes in Mathematics and its Applications book series (IMA, volume 162). Springer. 2018.

- Recommendations on policy designs and regulatory frameworks to allow market uptake of new stakeholders.

**List of key words**

Renewable energy, advanced prediction methods, control of distributed energy resources, local communities, local energy management, energy vectors, flexibility management, storage, demand control, flexibility incentives and markets, inter-community energy management, coordination, time scales, geographical scales, distribution grid, stability.

### 12.4.3 CP 3: Technological Solutions for the digitalization of Smart Energy Systems

#### Proposed title for the “call for proposals”

#### CP 3: Technological Solutions for the digitalization of Smart Energy Systems

Year of Launch	Budget allocation
T0+3 Months	3.16 M€

#### Context presentation

Our energy infrastructures will be facing to profound changes in the next decades. Indeed, the European energy landscape has been greatly disrupted, following citizens' aspirations for sustainable development, quantified objectives in terms of mitigating global warming and the decentralization of the renewable energy production (REN) and storage. The initiation of this energy transition took root in the opening of energy markets, which has boosted investment in new means of production and consumption by citizens over the past two decades. This contributes to a major upheaval on several fronts, namely the so-called 4D revolution (Decarbonization, Decentralization, Digitalization and Democratization). For example, the fast growing of the renewable share in the production of electricity requires to find new solutions to secure the energy systems with respect to the variable production of REN (including both electricity, gas and heat carriers), the stability and the balancing of the electrical system and the protection of the grid infrastructure itself.

As a key enabler, the ICT (information and communication technologies) sector had been supporting the optimal operation of network use for decades. It is now nevertheless facing major challenges to bring specific features. The challenges are in the scope of Service Level Objectives (SLO) (high reliability, high performances related to latency) but as well as intrinsic properties such as transparent deployment and upgrade, perturbation proof, multi-infrastructure awareness among others.

The call for proposals is complementary to the specific project targeting real time operation with legacy components and high reliability components and communication services.

#### Positioning with respect to the state of the art

Regarding the modelling and the management of the energy systems, the ambition of this call is to challenge the main international R&D players in this domain which are :

- energy companies and network operators such as RTE and EDF R&D in France or E.ON in Germany,
- manufacturers such as Schneider Electric, Siemens, General Electrics among others,
- as well as research institutes such as the INESC Tech in Portugal, NREL and SANDIA Labs in the United States, the Fraunhofer Institutes in Germany, AIT in Austria and VTT in Finland. At the international level, the Argonne National Laboratory is one of the most recognized multidisciplinary research centers in the field of energy systems.

Reliability and security of our modern power systems are raising major issues due to the existing interdependencies and their critical infrastructure rating<sup>132</sup>. For many years, the trend was to size the power system with the peak power, being then proof to almost all exceptional events. Since some years, and in order to reduce the investment costs, Operators are applying ICT tools to operate their assets to their limits<sup>133</sup>. This leads obviously to additional risks and both generic and specific ICT enablers must be ready to offer the right solution to the right problem.

Cyber-Physical Systems (CPS) for energy is an additional raising concern as well due to the complexity of the energy systems of systems. First level of hardening is obviously cybersecurity, covered for Power Systems by IEC standards<sup>134</sup>, which is not the purpose of the call. The aim is to support Operational Technologies for real time control and protection (versus classical IT) that can be distributed. This distribution of intelligence aims to reduce the risk of complex CPS and increasing the efficiency of local decision to manage infrastructures and associated flexibilities<sup>135</sup>.

Deployment and materials are critical issues for power system operators. Even if digitalization is a running process in most utilities, Operational Technologies (OT) systems are complex and distributed control and protection functions can be nightmare to develop and implement in the field. Some efforts at modelling side and self-implementations (on specific field devices) should be performed. This will support materials selection and Service Level Objectives to be requested to the telecommunication companies (TelCo).

The concept of Digital Twin is being developed in the energy sector with strong trends associated with the behavior modelling and the digital technologies spreading to consumers<sup>136</sup>. The first digital twin platforms appeared in smart grids in China<sup>137</sup>. The scientific bottlenecks of the digital twins rely in several domains: connectivity, modelling, instrumentation, data processing, architectures, algorithms and cognitive sciences<sup>138</sup>.

Scientists in computer science from CNRS, CEA, INRIA or University research units have already been strongly involved in the definition of the targeted projects and call for proposals (especially in TP3, CP2 and CP3). CP3 is a call on Technological Solutions for the digitalization of Smart Energy Systems. We expect from this call many proposals from computer science teams together with experts in power systems.

## Detailed topics

Keeping the global challenges in mind, there are some essential questions that should be addressed in this call: modelling of the energy Cyber Physical System of Systems, ensuring the continuity Edge-Cloud in a more decentralized system, virtualizing of the different control layers, as well as representing the multi-energy grid infrastructures by a digital twin.

The first topic is related to **reliability and security** of our modern infrastructures:

1. Fail safe modes and redundancy on both hardware and software
2. Tools for modelling of the Smart Grid Architectures (interoperability, flexible operation, Cost Benefit Analysis, security by design...) and tools to assess the

<sup>132</sup> Julia Matevosyan et Al. « Operational Security » IEEE Power and Energy magazine, Vol19 N2 March/April 2021

<sup>133</sup> Jacob Ostergaard et Al. « Energy Security Through Demand Side Flexibility » IEEE Power and Energy magazine, Vol19 N2 March/April 2021

<sup>134</sup> <https://sync-se.iec.ch/deliveries/cybersecurity-guidelines/>

<sup>135</sup> Michael Z Liu et Al « Grid and Market services from the Edge » IEEE Power and Energy magazine, Vol19 N4 July/August 2021

<sup>136</sup> Abiodun E. Onile, Ram Machlev, Eduard Petlenkov, Yoash Levron, Juri Belikov. Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review. Energy Reports 7 (2021) 997–1015

<sup>137</sup> Zhou, M., Yan, J., Feng, D., 2019. Digital twin framework and its application to power grid online analysis. CSEE J. Power Energy Syst. 5 (3), 391–398

<sup>138</sup> Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., Nee, A., 2019. Enabling technologies and tools for digital twin. J. Manuf. Syst. <http://dx.doi.org/10>

<p>compliance of a system of distributed systems, components and processes with regard to international reliability and security standards (e.g. IEC)</p> <ol style="list-style-type: none"> <li>3. Consumer data protection and users' privacy preservation, privacy-preserving energy trading (multi-actors energy trading in several contexts).</li> </ol> <p>The second topic is about <b>new Cyber-Physical Systems architectures for distributed intelligence</b>:</p> <ol style="list-style-type: none"> <li>1. Continuum Cloud-Edge-Devices, distribution of intelligence, new specific advanced ICT functions and real-time distributed database</li> <li>2. On the fly data processing for specific/related communication networks and learning on the edge for real time reaction</li> <li>3. Secure and privacy-preserving federated learning for real time attacks' detection and securing edges/end devices for energy Cyber-Physical Systems</li> </ol> <p>The third topic is about <b>easy deployment and materials</b>:</p> <ol style="list-style-type: none"> <li>1. Digital control and communication virtualized for easy deployment, consistent and inter-connectable software components, model driven system engineering to enable dynamic reconfiguration</li> <li>2. High performance infrastructure for both control and protection specific features (considering the environmental impact of this infrastructure), low cost infrastructure for large scale coordination (Service Level Objective about latency and/or reliability)</li> </ol> <p>The fourth topic is about <b>sizing and design of Digital Twins</b> for multi-energy systems:</p> <ol style="list-style-type: none"> <li>1. Tools for modelling and design of the ICT architecture of a digital twin for multi-energy systems (challenge the interconnections of Cyber-Physical components and models in real time, the communication and control interfaces, create joint solvers)</li> <li>2. Digital twins multi infrastructures for sizing ICT services (e.g. which SLO, which medium term planning for ICT and Energy)</li> <li>3. Real-time multi-energy digital twin for test, control, training and multi-objective optimization applications</li> </ol> <p>Functional DT (simulation of the functionalities provided by the system), control/command DT (simulation of the control architecture piloting the system), communication DT (simulation of the network infrastructure) or sensor DT (simulations of the sensor fetching the environment data) are particularly of concerns in this topic.</p> <p>Proposals need not address all the topics of the call. However, if some important topics were missing, some of the available funding would be reserved for a second call for proposals targeting the missing topics.</p>
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Expected results
<p>Advances of research are expected in several scientific and technological domains as :</p> <ul style="list-style-type: none"> <li>- tools for modelling, comprehension and design of complex multi-level, multi-energy systems architectures with distributed production/storage/conversion units;</li> <li>- innovative control strategies relying on flexible operation opportunities and multi-objective optimization;</li> <li>- new edge computing architectures supporting distributed intelligence for smart grids;</li> <li>- virtualization methods and techniques for Plug&amp;Play communication and control of the energy system devices;</li> </ul>

- “real-time” digital twin embedding the ICT architecture which connects the energy components. State estimation of Smart Energy Systems, and formal methods for designing the monitoring infrastructure with guaranteed system observability.

**List of key words**

Smart Energy Systems; District Energy Networks; Information and Communication Technologies; Service Level Objectives; Cyber Physical System of Systems; Service Oriented Architectures; Model Based System Engineering; Embedded Systems Secure and Predictable; Reconfigurable Mesh Communication Networks; Distributed architectures to manage grid complexity and Plug&Play A.I.; Multi-objective Optimization; Compliance with regard to international standards; State estimation for integrated energy systems



#### 12.4.4 CP 4: Innovative approaches to reduce or substitute critical materials in the transparent conductive layers and metallic contacts of solar cells

##### Proposed title for the “call for proposals”

**CP 4: Innovative approaches to reduce or substitute critical materials in the transparent conductive layers and metallic contacts of solar cells**

Year of Launch	Budget allocation
T0+3 Months	1.52 M€

##### Context presentation

In order to contribute to the Paris agreement targets regarding the limitation of the global warming, the solar cells annual production capacities may be multiplied by 20 (~3 TW) in 2030. This growth of the PV industry raises key issues regarding the tolerable contents in critical and scarce materials in the devices. More precisely, according to recent studies (e.g. Y. Zhang, Energy Environ. Sci., 2021), the silver (Ag) and indium (In) contents should not exceed 2 mg/W and 0.38 mg/W, respectively. As an example, it means Perovskite/silicon tandem cells cannot afford a total In-rich transparent conductive oxide (TCO) thickness thicker than 6 nm (B. Hallam, Silicon PV 2021), while up to 200nm/cell are currently used for high efficiency technologies. In-rich TCO layers serving as electrodes but also as recombination layers in multi-junction cells, almost all the post-PERC technologies (Passivated Emitter and Rear Contact cells) will face this In-content reduction challenge. A similar situation holds true for Ag, widely used as metal electrodes in post-PERC architectures, with for instance about 33.9 mg/W of Ag in heterojunction cells (SHJ). Therefore, we must consider disruptive approaches for In and Ag content reduction or substitution to ensure TW-scale PV sustainability. These approaches can either rely on new cell architectures (e.g. ITO / dielectrics stacks, TCO-free heterojunction), or on replacing the In-rich & Ag-rich layers by other materials (e.g. Ag substitution by Cu, Cu alloys or Al). This raises important scientific and technological challenges, for instance: i) direct contacting of thin active layers (a-Si,  $\mu$ c-Si, poly-Si) by metallic electrodes, ii) development of In-free transparent electrodes for heterojunctions (SHJ) and tandems, iii) influence on the module assembly process and reliability, iv) compatibility with large area, high throughput and low cost processes.

##### Positioning with respect to the state of the art

Ag & In contents in current industrial SHJ solar cells are about 33.9 mg/W and 10.74 mg/W, respectively, whereas the target for a sustainable PV industry would be about 2 mg/W and 0.38 mg/W. The project proposals should propose clear paths for reaching such targets.

Interesting processes (e.g. electroplating) were developed for the substitution of Ag electrodes by Cu. However, these processes have not been transposed into mass production, essentially because of reliability issues, environmental constraints (management of electrolyte solutions) and the lack of cost-effective processes, particularly when the electrodes are deposited on TCO films (additional masking/patterning steps needed). Therefore, the proposals should bring breakthrough approaches, processes and equipment for replacing Ag by more sustainable metals, such as Cu or Al or Cu alloys to prevent Cu ions diffusion

Recently, a proof-of-concept of SHJ cells without front TCO was demonstrated (S. Li, Joule 2021). However, the front contacting was obtained via processes non-compliant with future industrializations. Thus, the proposals should provide further understanding into the properties of the metal / thin active layers interfaces (e.g. passivation, metal diffusion), supporting the development of innovative approaches (new materials as electrodes) and deposition processes which could feature a better compatibility with the expectations of the PV industry.

Several investigations were conducted for the substitution of ITO by Al- or B-doped zinc oxides. However, there are still carrier transport and stability issues to be understood and solved with such materials. Furthermore, other advanced materials could be investigated.

Depending on each technology, oxides with the appropriate characteristics need to be available (energy levels, work function, doping level, chemical compatibility...). While efficient n-type TCOs are available, p-type TCOs still need significant further development and research. It should be noted that TCOs can be conceived to not only provide simple electrical conductivity but also become multifunctional by playing an active role in the solar cell, either by being part of the absorber or the junction itself. Dopant-free Asymmetric Heterocontacts (DASH) solar cells have become quite effective (J. Bullock Nature Energy 2016) and thus TCOs can play a role in the active structure of novel solar cells in the same way.

The use of oxides as photon absorbers in the solar cells is also expanding, where oxide perovskites and ferroelectric oxides (R. Nechache Nature Photonics 2014) are envisaged to surpass halide perovskites in terms of stability and toxicity, with the promise of open circuit voltages much higher than the bandgap of the absorber (S. Y. Yang, Nature Nanotech. 2010).

Proposals will also tackle these issues in the specific framework of tandem solar cells, where novel architectures may bring new challenges or open new opportunities. As an example the recent efficiency records for perovskite/silicon tandem devices were obtained with ITO films as recombination layers. Thus, proposals are expected to develop innovative approaches that will allow similar efficiency values, but by replacing the ITO films by In-free recombination layers or via advanced tunneling-assisted recombination processes (e.g. via Si-based junctions or directly at the interface between the electrode/hole collectors of the sub-cells).

#### Detailed topics

- **Ag-free or Ag-poor electrodes for high efficiency solar cells:** Development of alternative processes for eco-friendly & cost-effective Cu or Al deposition on TCO.
- **In-poor high efficiency solar cells:** Advanced cell architectures (including tandem) limiting the use In-based TCO, including highly performing p-type TCOs, TCOs with enhanced multifunctionality playing an active part in photocarrier generation or extraction. Designed via numerical simulations and experimental studies.
- **Direct contacting of thin active layers by metallic electrodes:** in-depth understanding of the properties of metal/semiconductor interfaces development of specific interface layers, new equipment & processes for localized contact to save materials, low-damage metal depositions, and direct process not requiring patterning steps.
- **Combining TCO/dielectric:** mastering interactions of the multi-layer materials, substitution of In-rich TCO by In-free materials (AZO, graphene).

#### Expected results

The mains expected results for the AAP are described hereafter:

- The overall targets of scarce material reductions should be oriented (principally but not exclusively) toward Solar cells with Ag & In amounts below 2 mg/W and 0.38 mg/W, respectively and  $\eta > 24\%$ . Ideally using a technology that does not require high temperature treatment, nor an aggressive process for reduced environment impact.

The main task identified are:

- Develop Ag-poor electrodes by alternative processes with better material yield, by silver substitution partial or total. Criteria of achievement will be based on above material usage mg/W. Beginning TRL2/3, End TRL3/4.

- Develop In-poor high efficiency solar cells by alternative processes with better material yield, by In substitution partial or total. Criteria of achievement will be based on above material usage mg/W. Beginning TRL2/3, End TRL3/4.
- Research on direct contacting of thin active layers by metallic electrode. Using experiments and modelling, develop specific interfaces and soft deposition approaches. Beginning TRL1/2, end TL3/4. Evaluate scarce material reduction (mg/W saved) vs cell performance.
- Develop innovative thin layer stacks (meta materials?) that combine TCO (In-poor) and Dielectric with electrical/optical properties adapted to solar structures. Beginning TRL1/2, End TRL 3/4... Evaluate scarce material reduction (mg/W saved) vs cell performance.

Proposals need not address all the topics of the call. However, if some important topics where missing, some of the available funding would be reserved for a second call for proposals targeting the missing topics.

**List of key words**

Solar cell, Solar module, Scarce materials, Silver, Indium, Copper, Electrode, Transparent Conductive Oxide, Recombination junction, Aluminum, Metallization, Contacting, Equipment, Tandem, Carrier transport

## 12.5 ANNEX 5: CALLS for EXPRESSIONS of INTERESTS (CEI)

## 12.5.1 CEI 1: Social science and humanities issues on advanced technologies for energy systems

Proposed title for the “call for expression of interest”
<b>CEI 1: Social science and humanities issues on advanced technologies for energy systems</b>

Year of Launch	Budgetary allocation
T0	4.29 M€

Context presentation
<p>All the objectives set by the PEPR TASE (innovation in the photovoltaic sector, development of floating wind power, integration and management of renewable energy in the networks) contribute to the structural modification of energy systems from a social, economic, spatial, and legal point of view (decentralized production, new uses, self-consumption, energy communities, digitalization)<sup>139,140,141</sup>.</p> <p>This call aims to renew the analytical frameworks and models used by the human and social sciences and thus understand and support the deployment of innovative technological projects<sup>141,142</sup>. The approach here will consist of reflecting on the dynamics of conception and appropriation of technology and their social impacts. This call encourages interdisciplinary co-construction (sociology, geography, planning, urbanism and architecture, psychology as well as political, economic, design, and management sciences)<sup>143</sup> around four themes that are transversal to the three subjects (floating wind, solar, networks) and a methodological axis. These identified themes constitute very current research fronts, in which the proposal will be in line with a logic of complementarity to the research networks/communities and with the idea of bringing out subjects that the research networks have not yet addressed.</p>

Content of the call for expression of interest
<p><b>1° New forms of energy generation and consumption.</b> This axis examines the technical, legal, economic, and sociological issues of new decentralized ways of producing and consuming energy (economic and legal structures, actors, pricing of access to and use of general public networks, microgrids, implications on uses and consumption, etc.), where consumers are themselves producers. The research will investigate how consumption could be adapted to production in a</p>

<sup>139</sup> GIEC, 2018 : Résumé à l'intention des décideurs, Réchauffement planétaire de 1,5 °C, Rapport spécial du GIEC sur les conséquences d'un réchauffement planétaire de 1,5 °C par rapport aux niveaux préindustriels et les trajectoires associées d'émissions mondiales de gaz à effet de serre, dans le contexte du renforcement de la parade mondiale au changement climatique, du développement durable et de la lutte contre la pauvreté [Publié sous la direction de V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor et T. Waterfield]. Organisation météorologique mondiale, Genève, Suisse, 32 p.

<sup>140</sup> Valentine, SV, MA Brown, and BK Sovacool. Empowering the Great Energy Transition: Policy for a Low-Carbon Future (New York: Columbia University Press, 2019)

<sup>141</sup> Nadai, Alain ; Labussière, Olivier. 2018, Energy transitions. Palgrave Macmillian

<sup>142</sup> Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., Nykvist, B., Pel, B., Raven, R., Rohrer, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: State of the art and future directions, Environmental Innovation and Societal Transitions, 31, 1–32. doi: 10.1016/j.eist.2019.01.004.

<sup>143</sup> McCauley, D., Ramasar, V., Heffron, R. J., Sovacool, B. K., Mebratu, D. & Mundaca, L. 2019. Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. Applied Energy. 233-234, p. 916-921.

context of total or relative autonomy, through the development of new practices, new representation, new values, energy communities.

**2° Articulation renewable energy (RE) generation- grids- uses.** This axis will deal with the principles and conditions of the balance between renewable energy generation and consumption at different scales of the grids. It will study the modes of governance, the articulation between political choices, market design and regulations (supply issues, financing, values) that this new balance implies, as well as the impacts on the configuration of the networks, which are moving from an integrated model to a distributed model and the new associated services (flexibility, load shedding, prosumer).

**3. Energy use situations.** This axis will examine the role and limits of the new energy use (mobility, communities, flexibility, etc.) in order to improve the energy system: overall use of the various energy vectors (gas, heat, biomass, electricity), integration of intermittent energies and balance of power systems. These uses are obviously linked to different human practices and activities whose organization and temporality are subject to numerous constraints that must be identified and questioned.

**4° Energy futures.** This axis aims to contribute to research on the scenarisation of the energy transition by focusing on ethical and justice issues, public perceptions, dynamics of adherence and the conditions for organizing public debates on the technical and economic scenarios of energy production, distribution, and consumption.

**Within this thematic framework, the call for expressions of interest aims to bring out targeted projects.**

In that perspective, **several methodological conditions are required.** Firstly, the work must be technically based, in line with the research carried out in the framework of the PEPR TASE. Secondly, the work must be interdisciplinary between humanities and social sciences or between humanities and social sciences and science and technology. Thirdly, this research should focus on crosscutting concepts and notions, allowing for interdisciplinary work. In this respect, the study could focus on the notions of materiality, commons, resource potential, socio-energetic assemblage, technical-economic approaches or modelling, or normativity. Finally, this research should assess the relevance of the current tools and indicators that support the energy transition. Thus, the work will mention the methods used to meet the scientific ambitions, particularly the data used (written data or collected data - survey, observations, focus group) or experimental processes (livings labs, experimental economics). The research related to science and technology will specify the concepts and working methods: for example, the cross-analysis of physical monitoring and social observation, the construction of resilience indicators, criticality and failure, etc.

#### List of key words

Social and human sciences, interdisciplinary, RE, grids, uses, energy futures, governance, recomposition, appropriation, integrations, solidarity, prosumer, citizens, energy communities

## 12.5.2 CEI 2: Resilience of electrical grids with massive renewables

**Proposed title for the “call for expression of interest”****CEI 2: Resilience of electrical grids with massive renewables**

<b>Year of Launch</b>	<b>Budgetary allocation</b>
T0	2.53 M€

**Context presentation**

Electric power systems are constantly subject to operational hazards and disturbances due to load variability, non-dispatchable renewable energy production and extreme weather phenomena, which can lead to rotating blackouts and ultimately to catastrophic events such as total blackouts<sup>144,145</sup>.

In Europe, the evolution toward a larger share of renewable energy sources, the multiplicity of different economic and technical agents, and the higher probability of extreme weather events driven by anthropogenic climate-change will increase the risks of partial or total blackouts in the future. More intermittent systems, whose production modes are diverse and submitted to meteorological conditions and hazard (renewable energy), will be connected to the distribution/transmission systems. The demand will also globally increase as well as its random fluctuations, the latter driven by the time and space dependent features of the networks.

The CEI aims at gathering a consortium able to propose multi-disciplinary models and methods to increase the resilience of future electricity networks<sup>146,147</sup>, focusing on the hazard introduced by the increase of extreme weather<sup>148</sup> events due to climate change, and on a massive use of renewable energy sources<sup>149</sup>.

**Content of the call for expression of interest**

The expected output of this call is a consistent set of predictive and prescriptive models, policies, and regulations to ensure the resilience of future electric power systems, with a focus on methodologies that are robust to prediction errors. This can be achieved by gathering a multi-disciplinary consortium including specialists able to address the following issues:

- To predict rare weather climatic events in a changing climate, identify possible critical scenarios of compound weather events which can put at risk energy production at a regional scale: extract data from global and regional climate models, perform bias corrections and downscaling to derive the relevant variable to model the energy capacity,

<sup>144</sup> J. W. Busby et al., “Cascading risks: Understanding the 2021 winter blackout in Texas,” *Energy Research & Social Science*, vol. 77, p. 102106, Jul. 2021, doi: 10.1016/j.erss.2021.102106.

<sup>145</sup> Y. Wang, C. J. Wang, and R. Baldick, “Research on Resilience of Power Systems Under Natural Disasters—A Review,” *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1604–1613, Mar. 2016, doi: 10.1109/TPWRS.2015.2429656.

<sup>146</sup> M. Panteli and P. Mancarella, “The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience,” *IEEE Power and Energy Magazine*, vol. 13, no. 3, pp. 58–66, May 2015, doi: 10.1109/MPE.2015.2397334.

<sup>147</sup> B.-J. Jesse, H. U. Heinrichs, and W. Kuckshinrichs, “Adapting the theory of resilience to energy systems: a review and outlook,” *Energ Sustain Soc*, vol. 9, no. 1, p. 27, Dec. 2019, doi: 10.1186/s13705-019-0210-7.

<sup>148</sup> M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, and P. Mancarella, “Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures,” *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3747–3757, Sep. 2017, doi: 10.1109/TPWRS.2016.2641463.

<sup>149</sup> M. Mahzarnia, M. P. Moghaddam, P. T. Baboli, and P. Siano, “A Review of the Measures to Enhance Power Systems Resilience,” *IEEE Systems Journal*, vol. 14, no. 3, pp. 4059–4070, Sep. 2020, doi: 10.1109/JSYST.2020.2965993.



its fluctuations and the possible hazards of a network based on renewable power generators.

- To characterize, model and simulate the impact in the electrical grid of these predicted events and how the massive share of renewable power generators may impact the blackout risks.
- To analyze historical data and past blackouts on similar electrical grids in order to validate to models developed.
- To produce blackout propagation scenarios and estimate their probability of occurrence, to identify scenarios whose probability of occurrence is significantly increased by massive introduction of renewable energy.
- To produce blackout propagation scenarios and to investigate the social and economic consequences of a blackout, and the influence of the market on the blackouts.
- To optimize realistic and fair recovery plans through technical reconfiguration strategies, for selected blackout scenarios, revisit investment strategies and market regulation to account for these new recovery plans.

#### List of key words

Blackout, compound weather extreme events, climate change, economic agents, electrical engineering, interdependencies, complex systems, market design, operation research, power system, renewable energy, resilience, risk, stochastic modelling, vulnerability

## 12.5.3 CEI 3: Low carbon footprint and recycling PV Module

<b>Proposed title for the “call for expression of interest”</b>
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<b>CEI 3: Low carbon footprint and recycling PV Module</b>
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Year of Launch	Budgetary allocation
T0	1.43 M€

**Context presentation**

Recent life cycle analysis (LCA) have shown that landfilling of c-Si PV panels is still the most preferred waste management strategy while considering only the economic factors. This emphasizes the need to curtail landfilling through regulatory restrictions and enhance the recyclability of next solar panel generation together with the reduction of the amount of material needed for their construction.<sup>150</sup> In order to drastically reduce the environmental footprint of PV modules, several options have to be explored for both the current and the future technologies. Currently, glass encapsulation concentrates about half of the energy used within the manufacture of the silicon PV module. With the sake to reduce environmental footprint, there is an important need to rethink the modules fabrication with the goal to limit the amount of materials used, their origin (ie. minerals, fossil-based or biomass) and the energy required for their implementation. Typically, the energy payback time (EPBT) depend on the technology and on the localization of the PV modules. In southern Europe (with a sun irradiation of 1700 kWh/m<sup>2</sup>/year) monocrystalline silicon PV modules have an EPBT of about 1 year<sup>151</sup>. The new thin film technologies combined to the management of materials recovery, retreatment and reintroduction into a new life cycle will drastically reduce the gray energy of future PV modules.

This call for expression of interest is focusing on the reduction of the environmental footprint through saving materials and in accelerating in the concept of eco-conception of future PV modules. For this, a particular emphasizes is given to the substrate and the encapsulation for the new thin film technologies. Obviously, the properties of such innovative materials have to match with their principal function in the PV modules,<sup>152,153</sup> e.g. excellent barrier to humidity, oxygen, both thermal and photostability while being inert with the active materials in contact<sup>154, 155</sup>. While there has been few or no alternatives to investigate biofilms in optoelectronics, a new paradigm has to be reached for solar panels targeting water and dioxygen barrier films from biomass and/or recycled materials along with life cycle and recycling considerations.

**Content of the call for expression of interest**

The call addresses new materials and processes for the future module substrates and encapsulation. The goal is to strongly reduce the environmental footprint of the next generation of solar modules. Strong collaboration between chemists, material scientists, physicists and electrical engineering scientists is expected to solve the PV module ecoconception challenge. Expectations for materials and processes are:

- The new materials (substrates and encapsulation) must avoid as much as possible the use of rare, critical raw and/or fossil-based materials
- Their implementation will not require the use of toxic solvents.

<sup>150</sup> K. Ganesan et al. *Energy* 245, 123207 (2022)

<sup>151</sup> <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

<sup>152</sup> IEC 61215–1:2016 Terrestrial Photovoltaic (PV) Modules - Design Qualification and Type Approval - Part 1: Test Requirements (IEC Webstore, 2016); <https://webstore.iec.ch/publication/24312>

<sup>153</sup> IEC 61215–2:2016 Terrestrial Photovoltaic (PV) Modules - Design Qualification and Type Approval - Part 2: Test Procedures (IEC Webstore, 2016); <https://webstore.iec.ch/publication/24311>

<sup>154</sup> M. O. Reese et al. *Sol. Energy Mater. Sol. Cells* 95, 1253–1267 (2011).

<sup>155</sup> M.V. Khenkin et al. *Nat Energy* 5, 35–49 (2020).

- The recycling and the life cycle assessment of the newly designed materials will be considered
- The applicants will specify the technologies for which the proposed materials can be targeted taking into account specificities. For instance :
  - in the case of perovskite PV technology, substrates and encapsulate have also to prevent the interdiffusion of halogen and lead elements.
  - in case of OPV, temperature and solvents of the substrates and encapsulate have to be compatible with active layer and top electrode

Finally, the life cycle analysis of the new materials and processes should be considered.

This call for expression of interest is to be coordinated with the other topics of the PEPR:

-it should preferentially be compatible with other technologies developed, such as tandems thin film on Si, and complementary to other topics already in the targeted project (PV-Tec.2)

<b>List of key words</b>
PV modules; New encapsulation materials; Transparent flexible substrates ; Environmental footprint reduction; Eco-design; Eco-conception; Life cycle analysis; Bio-sourced materials; Materials recycling; Materials reuse; Disassembling

## 12.5.4 CEI 4: Advanced Intelligent PV Module

Proposed title for the “call for expression of interest”	
CEI 4: Advanced Intelligent PV Module	
Year of Launch	Budgetary allocation
T0+24 Months	1.50 M€

Context presentation
<p>While strong efforts are being dedicated in the world to improve the efficiency and reliability of new solar cell technology, developments of new PV modules must be explored with new paradigms. First of all, because third generation of PV cells induce drastic changes on their optimal designs and possible associations inducing new trade-off and new need for electrical protections. For this purpose, PV modules must be involve with new innovative functions like sensors and switches directly integrated into PV modules to increase their robustness and life-in service and usages taking into account their performance in degraded modes.</p> <p>Thus, the association of integrated sensors, switches and communications tools in the same PV module makes it “smart” and potentially more pro-active with inverters or micro-processors or monitoring systems. However, intelligent with the help of sensors and interactive communications tools represent drastic technological challenges and explored researches to :</p> <ul style="list-style-type: none"> <li>- be able to interface and monitor PV cells with sensors and switches,</li> <li>- be able to enhance optimal performances of PV modules,</li> <li>- estimate the ratio complexity of processes/increase of performances.</li> </ul> <p>A particular focus will be done in this AMI project to integrate new innovative module bricks to result in new technologies, that are studied in the target project of the TASE PEPR project (PC2.2). The association of new innovations in all part of components included in a module will be the real complex problem to resolve compatible process.</p> <p>Modelling and characterization tools shall help to do trade-offs needed to design new modules including drastic changes.</p> <p>In PV area, even on first generation of Si Cells, very few studies have been done on new types of PV cells interconnections. In 2009, [1] showed how parallel connection of PV module were able to increase production. [2] and [3] present several cases of interconnections with comparisons of performances. [4] showed an other comparative study made by means simulations tools including by-pass diodes. One example of recent study have been done by [5] showing the advantages of reconfiguration dynamic PV array in cases of partial shadows. [6] proposes a new MPPT algorithm for TCT PV panels configuration and its pertinence in case of less PV production of one or several panels.</p> <p>[1] Parallel-Connected Solar PV System to Address Partial and Rapidly Fluctuating Shadow Conditions Lijun Gao, Roger A. Dougal, Shengyi Liu, <i>IEEE</i>, and Albena P. Iotova. IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 56, NO. 5, MAY 2009</p> <p>[2] Yaw-Juen Wang, Po-Chun Hsu. « An investigation on partial shading of PV modules with different connection configurations of PV cells. <i>Energy</i> 36 (2011) pp 3069-3078.</p> <p>[3] Smita Pareek, Ratna Dahiya. « Enhanced power generation of partial shaded photovoltaic fields by forecasting the interconnection of modules ». <i>Energy</i> 95 (2016) 561e572.</p> <p>[4] F. Belhachat C. Larbes « Modeling, analysis and comparison of solar photovoltaic array configurations under partial shading conditions. <i>Solar Energy</i> 120 (2015) 399–418.</p> <p>[4] M. Balato, L. Costanzo, M. Vitelli «Series–Parallel PV array re-configuration: Maximization of the extraction of energy and much more ». <i>Applied Energy</i> 159 (2015) pp 145–160</p> <p>[5] Shubhankar Niranjana Deshkar, Sumedh Bhaskar Dhale, Jishnu Shekar Mukherjee, T. Sudhakar Babu, N. Rajasekar «Solar PV array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm. <i>Renewable and Sustainable Energy Reviews</i> 43(2015) pp 102–110</p>

Content of the call for expression of interest

The call addresses new integrated functions on future PV modules able to improve power production and their reliabilities in several meteorology cases and adverse working conditions, but also to increase the potential lifetime. For that, a drastic change of perspective shall be done to design and optimize new generation of PV modules in particular in advanced solar cell technologies (thin films, tandem, and/or semi-transparent technologies...)

The goal of this CEI is to explore new co-designs and technical process able to reveal high performances on efficiencies and lifetime working in urban solar conditions with repetitive shadows and under non-ideal solar irradiation (eg. high level of dust, high percentage of atmospheric pollution or humidity), to achieve and prove the capacities of new modules to increase their long-term performance.

These procedures and methods will be based on technical process, experimental tests and numerical approaches :

- (i) Integrated sensors of performance related quantities (including but not limited to, e.g. temperature, current, voltage) using possibly thin film solar cell technologies, or technologies compatible with thin films devices.
- (ii) Design , realization and integration of switches TFTs, diodes adapted with existing connectors and new PV modules
- (iii) New tools to help the Optimization of the module interconnection designs taking into account as series/parallel/matrix configurations and their theoretical gains due to smart interconnect management
- (iv) New tools and algorithms able to estimate at each time the optimal interconnected configuration of PV cells
- (v) Communications tools able to control states of switches and export measurement data

In the end, the full project should aim at the achievement of new lab prototypes of smart PV modules including controlled switches, sensors, communications protocols and main improved technologies. This call for expression of interest is to be coordinated with the other topics of the PEPR: -it should preferentially be compatible with other technologies developed, such as tandems thin film on Si, and complementary to other topics already in the targeted project (PV-Tec.2) .

In the end, the full project should aim at the achievement of new lab prototypes of smart PV modules.

Answers can be proposed by a single team or a consortium and should address at least one item.

#### List of key words

Reliability; Integrated sensors of currents, voltage, temperature; Pro-active protections  
Switches & connectors; Communication techniques; Tests on shadow conditions  
New co-designs; In-situ/operando characterization; Thermal management; Electrical properties;  
Modelling; Artificial intelligence

## 12.5.5 CEI 5: reliability of advanced solar cell technologies

<b>Proposed title for the “call for expression of interest”</b>
<b>CEI 5: reliability of advanced solar cell technologies</b>

<b>Year of Launch</b>	<b>Budgetary allocation</b>
T0	5.05 M€

<b>Context presentation</b>
<p>While strong effort is dedicated to increase the efficiency of solar cells, a major issue for the development and expansion of new PV technologies is to control their reliability. In particular, before industrialization of new technologies, it is mandatory to be able to quantify their long-term robustness in varied service conditions, which requires understanding their degradation mechanisms and measure / model / predicting their degradation kinetics in function of external stresses.</p> <p>Standard reliability tests and protocols exist and are commonly used for the quality control of mature technologies, for which reliability is also verified by long-term outdoor exposure. The tests may need, however, to be revisited for new technologies or new applications (flexible PV, agriPV, floating PV) for which the degradation mechanisms and hence the main factors controlling degradation rates can be different. Moreover, new technologies cannot wait for decades for validation in operating conditions, while validation by a shorter outdoor exposure time needs to develop modelling strategies able to transpose short time results to long-term reliability.</p> <p>It is thus important to develop new approaches and propose new methodologies and analyses that can tackle the degradation issues at the material, interface, and device levels and take into account the degradation mechanisms relevant to different operation conditions, which should be considered in new accelerated aging procedures. Of particular interest are the <i>in situ</i>/operando characterizations allowing one to observe the initial stages of degradation, intermediate reactions and the effect of selected factors on the system evolution upon time. A combination of specifically relevant and complementary <i>ex situ</i> characterizations as well as the development of new numerical models will help to develop a predictive approach able to assess the most probable degradation mode and evaluate long-term durability.</p> <p>Various advanced <i>in situ</i>/operando characterization tools have emerged in the past decade, which have facilitated the understanding of the degradation mechanisms and the further development of high-performance batteries [1-5].</p> <p>The use of <i>in situ</i>/operando characterization tools has also been proposed recently in the field of photovoltaics, since they appear mandatory to analyze changes occurring during operation at the material and interface levels. Some recent work can be found especially for the study of the degradation of perovskite materials [6-12].</p> <p>However, the study of reliability and degradation of solar cells cannot be limited to such <i>in situ</i>/operando tools, and it also requires complementary <i>ex situ</i> multiscale characterization, from various advanced techniques [13].</p> <p>[1] P. Noval et al., "Advanced <i>in situ</i> methods for the characterization of practical electrodes in lithium-ion batteries", <i>Journal of Power Sources</i> 90 (2000) 52, <a href="https://doi.org/10.1016/S0378-7753(00)00447-X">https://doi.org/10.1016/S0378-7753(00)00447-X</a></p> <p>[2] J. Tan et al., "In <i>situ</i>/operando characterization techniques for rechargeable lithium–sulfur batteries: a review", <i>Nanoscale</i> 9 (2017) 19001, <a href="https://doi.org/10.1039/C7NR06819K">https://doi.org/10.1039/C7NR06819K</a></p> <p>[3] S-M. Bak et al., "In <i>situ</i>/operando synchrotron-based X-ray techniques for lithium-ion battery research", <i>NPG Asia Materials</i> 10 (2018) 563, <a href="https://doi.org/10.1038/s41427-018-0056-z">https://doi.org/10.1038/s41427-018-0056-z</a></p> <p>[4] A. M. Tripathi et al., "In <i>situ</i> analytical techniques for battery interface analysis", <i>Chem. Soc. Rev.</i> 47 (2018) 736, <a href="https://doi.org/10.1039/C7CS00180K">https://doi.org/10.1039/C7CS00180K</a></p> <p>[5] D. Liu et al., "Review of Recent Development of In <i>Situ</i>/Operando Characterization Techniques for Lithium Battery Research", <i>Advanced Materials</i> 31 (2019) 1806620, <a href="https://doi.org/10.1002/adma.201806620">https://doi.org/10.1002/adma.201806620</a></p> <p>[6] U.B. Cappel et al., "Partially Reversible Photoinduced Chemical Changes in a Mixed-Ion Perovskite Material for Solar Cells", <i>ACS Appl. Mater. Interfaces</i> 40 (2017) 34970, <a href="https://doi.org/10.1021/acsami.7b10643">https://doi.org/10.1021/acsami.7b10643</a></p>



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- [13] Advanced Characterization Techniques for Thin Film Solar Cells, edited by Daniel Abou-Ras, Thomas Kirchartz, and Uwe Rau, WILEY-VCH Verlag GmbH & Co. KGaA (2011)

### Content of the call for expression of interest

The call addresses the reliability issues in the materials and interfaces entering in new solar cell technologies. Studies on module encapsulants and interconnections are out of the scope.

The goal is to propose procedures and methods that can reveal, describe and understand degradation at early stages, identify factors responsible for the degradation and estimate their kinetics. Eventually one should be able to predict long-term performance of solar cells and possibly propose solutions for its improvement.

These procedures and methods can be based on experimental and numerical approaches and analyses of the degradation processes using:

- *In situ*/operando characterization tools where properties of the materials, interfaces, solar cell devices, can be tracked under relevant stressors (electrical, optical, thermal, environmental, mechanical, chemical) and combinations of these.
- Complementary *ex situ* characterization that can be performed at various stages of degradation, up to failure and post-failure analysis.
- Multiscale numerical modelling. It consists on one hand of theoretical calculations (ab initio, Monte Carlo...) to study the stability of materials and interfaces. On the other hand, numerical modelling based on data analysis from characterizations, including innovative algorithms and procedures, with potentially help of artificial intelligence can also be proposed.

The experimental procedures and methods aim at covering all the aspects and properties that can be impacted by or reveal degradation of the device's PV conversion ability: physico-chemical, structural, electrical, optoelectronic. The possibility to combine *in situ*/operando and *ex-situ* characterizations is a real added value. Particular attention should be paid on the reproducibility of measurements and reliability of the collected information.

In general, the stability of the devices is a multi-parameter space that depends on the stress conditions as well as on the process conditions for the thin film materials and interfaces forming the devices.

The applications should highlight the scientific competences of the research structure or consortium that will enable it to address at least one of the topics of the call and to provide relevant answers. They should also indicate on which kind of samples they will apply their study and how these samples will be provided.

### List of key words

Reliability, degradation, accelerated ageing  
Process dependent material and interface properties in solar cells  
Tests and protocols

*In-situ/operando* characterization  
Combined *ex-situ* characterizations  
Correlative analysis  
Structural, physico-chemical, electrical, optoelectronic properties  
Modelling at the fundamental level (ab initio, Monte Carlo...)  
Artificial intelligence coupled with physical modelling