“Innovation for Climate chAnge mitigation: a study of energy R&d, its Uncertain effectiveness and Spillovers“ is a three-year (2010-2012) European Research Center (ERC) Starting Grant funded by the European Commission under the umbrella of the 7th Framework Programme.

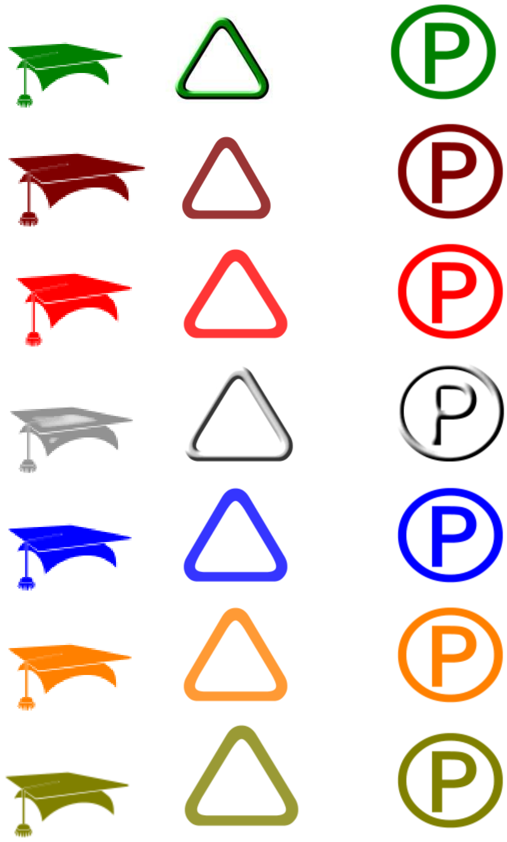
ICARUS survey on the current state and future development of SOLAR PV and CSP technologies

Technical report

Thank you again for the time you devoted to the survey. It helped us collecting a wealth of information that will prove very useful to assess the potential of solar technologies

Name and Surname	**Previous current affiliation**	**Country**
Arnulf Jäger-Waldau	Scientific officer at European Commission, DG JRC	Germany
Roberta Campesato	Space Unit Responsible at Centro Elettroteccnico Sperimentale Italiano (CESI)	Italy
Antonio Luque	Director of the Instituto de Energía Solar, Universidad Politecnica de Madrid (IES)	Spain
Rolf Wüstenhagen	Director, Institute for Economy and the Environment, University of St. Gallen	Switzerland
Carlos del Canizo Nadal	Universidad Politecnica de Madrid (IES)	Spain
Paolo Frankl	International Energy Agency (IEA)	UK
Ferrazza Francesca	Responsible for R&D Activities on Renewable Energy Sources at ENI	Italy
Paul Wyers	Joint Programme Coordinator at ECN	The Netherlands
Wim Sinke	Senior staff member Program and Strategy at ECN Solar Energy	The Netherlands
Rob Bland	McKinsey (Silicon Valley)	US
Ole Langniss	Fichtner - Engineering and Consulting Services	Germany
Aldo Di Carlo	Head of the Opto&Nanoelectronics group, UniRoma2	Italy
Luisa Cabeza	Professor on Thermal Engineering at the University of Lleida	Spain
Paolo Martini	ASE's Business Development at Archimede Solar Energy (Angelantoni Group)	Italy
Christoph Richter	German Aerospace Center, Institute of Technical Thermodynamics, Solar Research.	Germany
Roland Langfeld	Schott AG. Research and Technology Development.	Germany

Table 1: List of experts participating in the survey



	ACADEMIA	INSTITUTIONAL RESEARCH	PRIVATE SECTOR
EU (Institution)			
US			
Spain			
Switzerland			
Italy			
The Netherlands			
Germany			

Table 2: List of the chromatic symbols that have been used in the figures

The present document provides a preliminary analysis of the outputs of the expert elicitation survey, carried out within the 3-year ERC-funded project on innovation in carbon-free technologies (ICARUS - Innovation for Climate chAnge mitigation: a study of energy R&D, its Uncertain effectiveness and Spillovers - www.icarus-project.org).

Figure 1**Errore. L'origine riferimento non è stata trovata.** provides a graphical representation of the main solar technologies that have been assessed in the expert elicitation process.

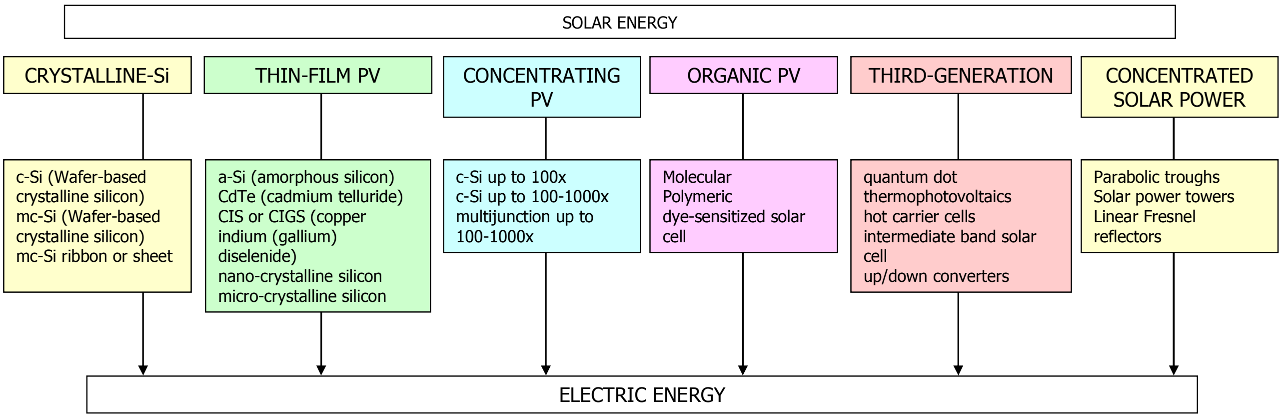


Figure 1: Technology paths that have been assessed in the interviews with the experts

Figure 2 illustrates the origin of the experts and demonstrates the heterogeneity of the cluster of experts, which was composed by an equal number of experts from the institutions, the universities and the private sector.

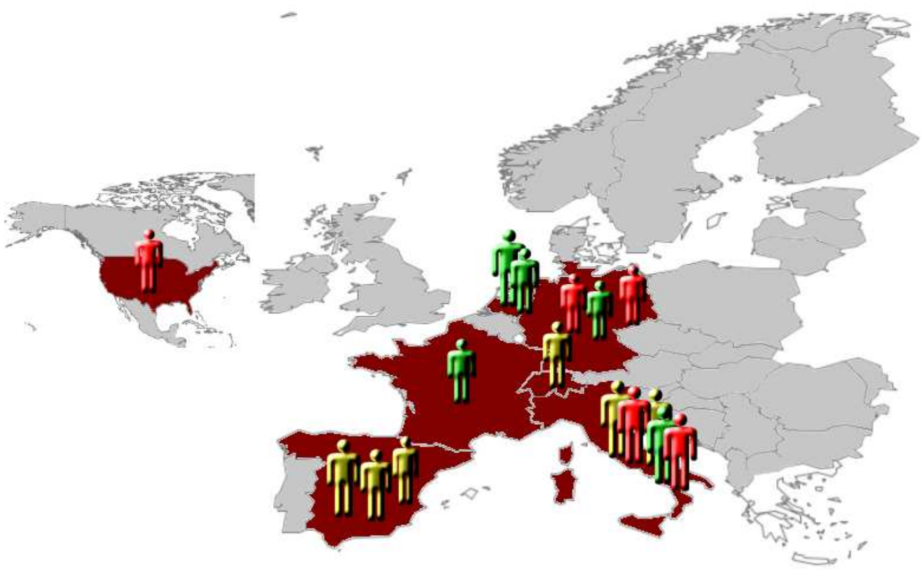


Figure 2: Geographical map of the areas of origin of the experts and of their professional sectors. The individual figures over each country indicate the number of experts per country, while the colours highlight their professional sectors: green = institution, yellow = academy, red = private.

Figure 3 compares the level of expertise of the selected experts, using the outputs of the self-evaluation exercise (see Annex I for the list of the symbols).

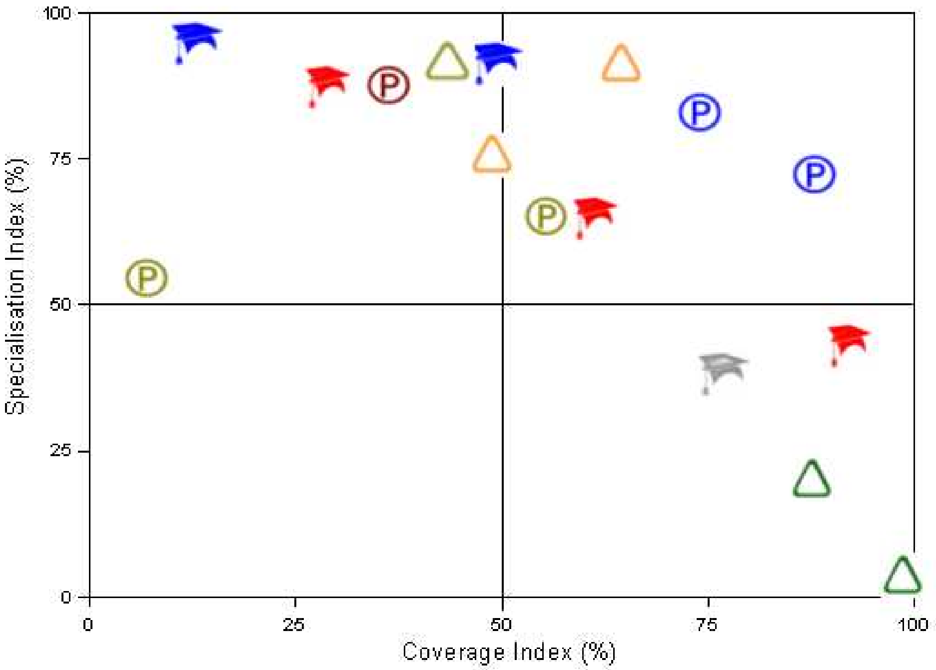


Figure 3: Direct ordination of the 16 experts based on the Coverage Index and the Specialisation Index.

The scatterplot area can be read as follows: (i) the high/left quadrant, identifying experts with low values of coverage and high level of specialisation, (ii) the high/right quadrant, including experts with high coverage and high specialisation; (iii) the low/right quadrant, with experts presenting high coverage with scarce specialisation; and (iv) low/left quadrant with experts characterized by low coverage and low specialisation.

The ordination shows that most experts have a high degree of specialisation (SI > 50%) whereas the wide spread along X axis suggests different levels of coverage for the solar technologies. It is to be noted that the experts' background seems to partially influence the specialisation and coverage: in fact, all the experts from the Private sector are highly specialised, whereas the two experts from the international institutions show high coverage of solar technologies knowledge (CI near to 100%) but as a whole low specialisation (SI < 25%).

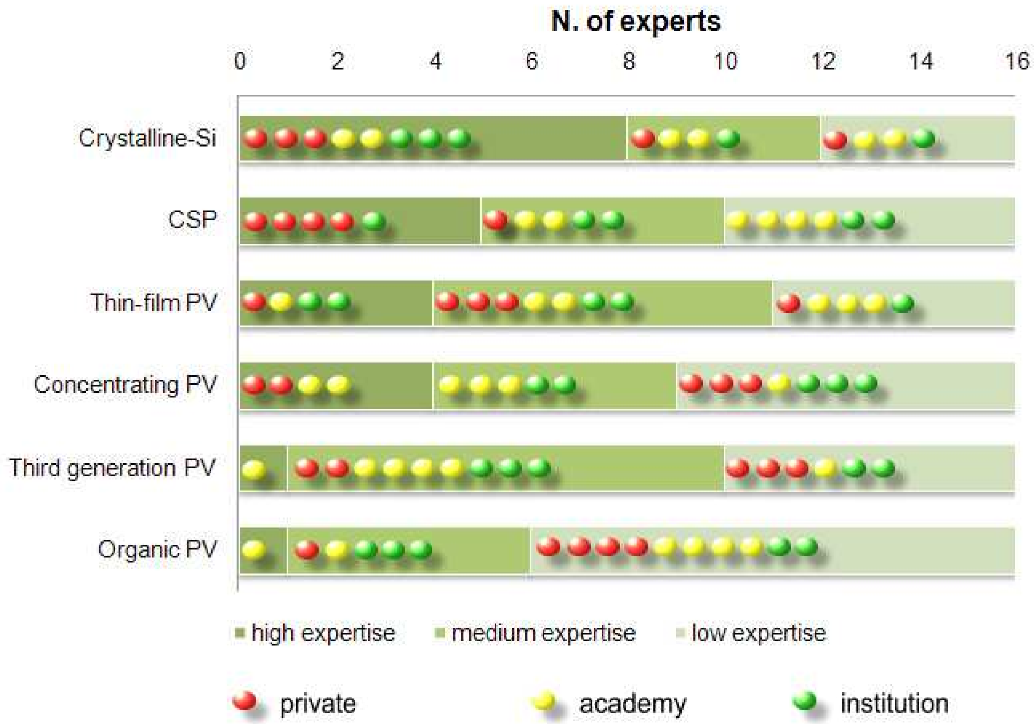


Figure 4: Distribution of the experts in three classes of expertise (High expertise: max level of knowledge >3; medium expertise: max level of knowledge =3; Low expertise: max level of knowledge <3) in the six major classes of solar technologies.

Most experts from different backgrounds declared to possess a high level of expertise on relatively mature solar technologies, such as Crystalline-Silicon and CSP, while a good knowledge on innovative technologies, such as Third Generation PV and Organic PV, was the prerogative of only a few experts, mainly academics (Figure 4).

1. Technical potential of solar technologies

The assessment of the possible drivers for the future variations in the cost of electricity produced with solar technologies started with the analysis of the current technical characteristics of each selected path. The experts provided important insights on which specific conditions would lead solar technologies to commercial success, and identified the stages of the RD&D process that had to be improved to overcome the existing bottlenecks.

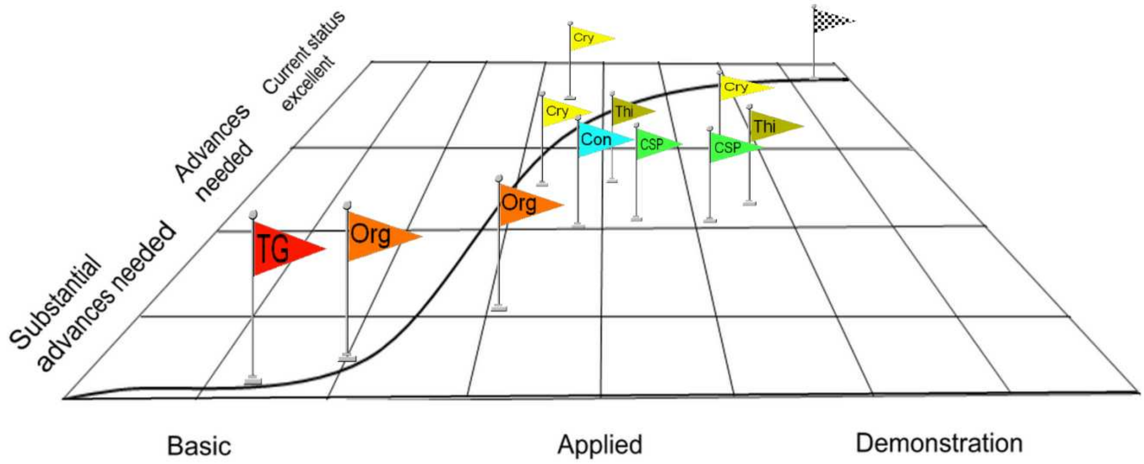


Figure 5: Pathway to commercial success. Relationship between the current maturity level of the different solar technologies and the type of RD&D funding helpful in overcoming the potential barriers to the commercial success identified by the experts. The dark continuous line shows the success line. Coloured flags used for the different solar technologies: TG, red = Third generation PV; Org, orange = Organic PV; Con, blue = Concentrating PV; Cry, yellow = Crystalline-Si; CSP, green = Concentrated Solar Power; Thi, lime green = Thin-film PV.

The experts generally agreed in allocating most of the budget to improve "mature" technologies (Figure 6), such as Crystalline Sylicon PV, Thin Film PV and CSP. For those technologies, the investments should mainly consist in engineering and applied R&D efforts.

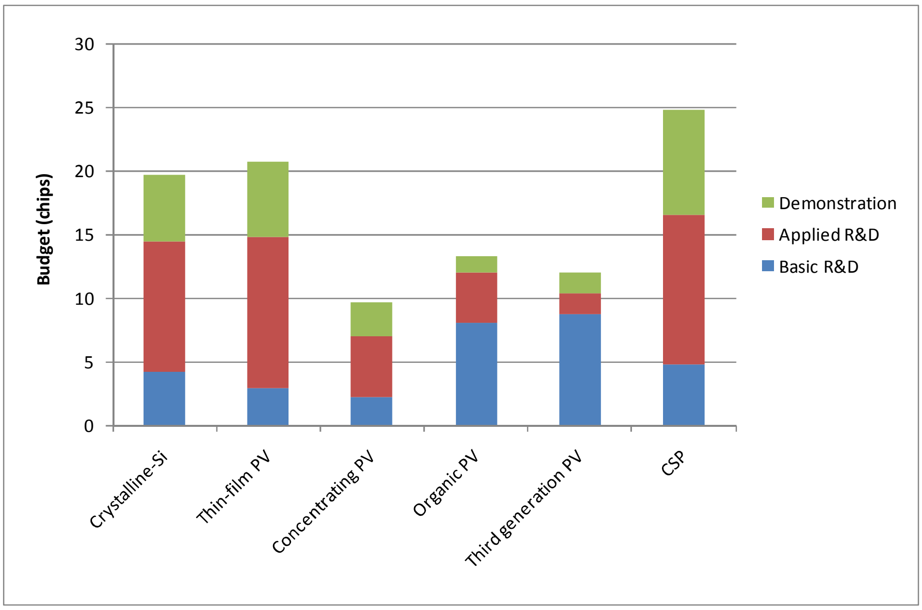


Figure 6: Allocation of the RD&D budget over the 2010-2030 period to make solar technologies commercially successful in 2030. The budget is conventionally expressed in 100 "chips" per expert, to be distributed among the different solar technologies.

The experts considered *CSP* technology as a promising choice. Thanks to its thermal storage and hybridisation possibilities, CSP provides firm dispatchable electricity, but it would still need high capital investments. Lowering the costs of CSP requires significant research and development efforts with respect to mirrors, heliostats, linear or point focus receivers, and power blocks. Main barriers to the success of CSP technologies are linked to the heaviness and big dimensions of the structures and to the necessity to demonstrate long term stability and efficiency on the field.

According to the experts, main advances in *Crystalline-Silicon* technology should derive from the automation of the production processes, and the introduction of more robust and durable encapsulation concepts. Cell efficiency should be increased above 20% (about 21% for mc-Si and about 25% for c-Si), reducing the large gap between laboratory efficiency and module efficiency. In general, all the experts are convinced that Crystalline-Silicon technology should be improved, and that the technical improvements need to be supported by a structured demonstration activity.

Improvements in the efficiency of the module up to 15-18% are considered crucial for successful *Thin Film* technology, and also the development of large-scale production units. The durability of the technology should be proven through specific demonstration tests. Overall, the costs and the time to market should be reduced to ensure its large-scale diffusion.

Advances in *Concentrating PV* technologies would seem to benefit from an integrated effort of basic and applied R&D and of demonstration activities. Applied R&D should lead to higher precision in manufacturing and higher quality of the technology. Demonstration of stability and efficiency should be carried out on the field and on the long term.

Organic PV and *Third generation PV* technologies were judged to need further development. In Organic PV technology major advances are needed to understand materials properties, and ensure a high level of reliability, stability and efficiency of the utility. Very high efficiencies could be achieved in Third Generation technologies, where innovative materials and devices are being processed at the nanoscale but are still in the exploration phase. A structured demonstration phase should be carried out to demonstrate the potentials and functionality of third generation technologies.

Testing for the independence of the budget distribution (n. of chips) and the expertise level one can see a significant association between the experts' level of knowledge in a specific technology and their budget allocation.

2. RD&D effectiveness on future solar technologies cost

Figure 7 reports experts' expected costs in 2030 (90th percentile, 10th percentile and "best guess") for different R&D scenarios.

In the first scenario the current annual level of RD&D would not change until 2030. The RD&D program would correspond to 350 millions of 2005USD. In the second scenario, the investment in RD&D for solar PV and CSP technologies would increase by 50% until 2030, and would therefore correspond to 525 millions of 2005USD. In the third scenario the investment in RD&D would increase by 100% in the next 20 years, reaching 700 millions of 2005USD.

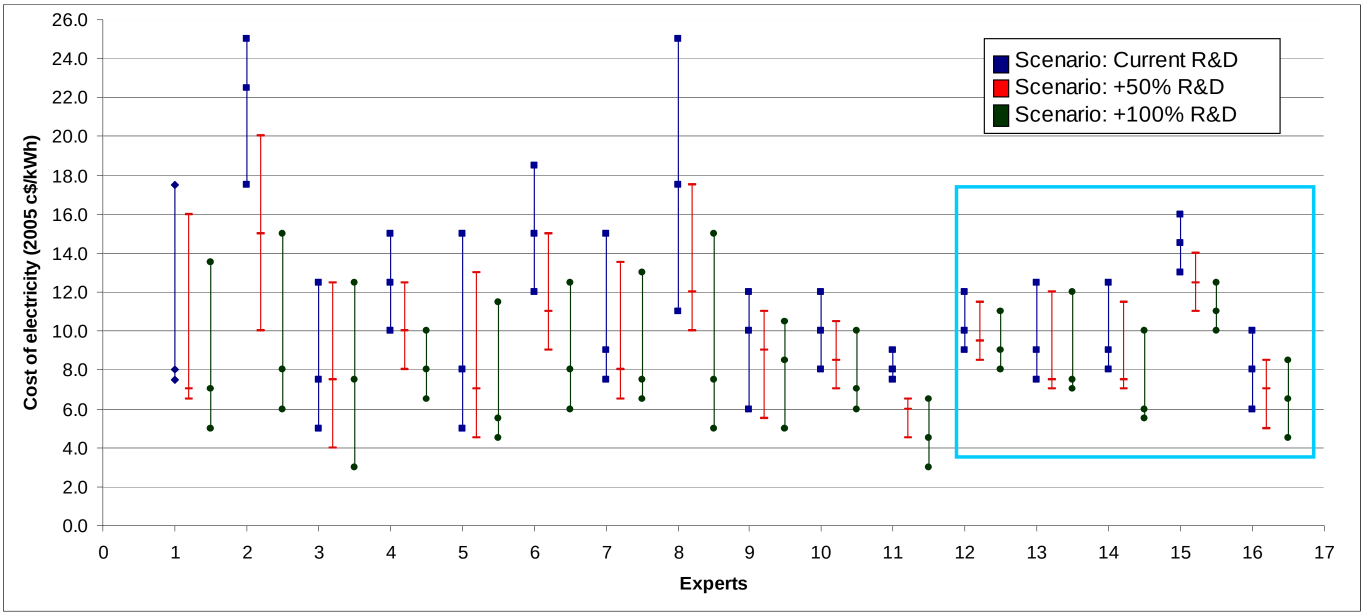


Figure 7: Estimates of electricity cost from solar technologies in 2030, under three different R&D funding scenarios. The blue area includes the experts who explicitly assigned cost values related to electricity generated from CSP. The other experts were referring to PV or to a mix of technologies.

Experts' estimates of the expected cost of electricity in 2030 (Figure 7) generally indicate a high degree of uncertainty, especially for PV technologies. Most estimates are comprised between 6 c$/kWh and 12 c$/kWh. The uncertainty tends to decrease when considering higher R&D investment scenarios (Figure 8). However, the increase in R&D does not seem to lead to important reductions in the expected costs (for both R&D scenarios most of the time the predicted reduction is less than 10%).

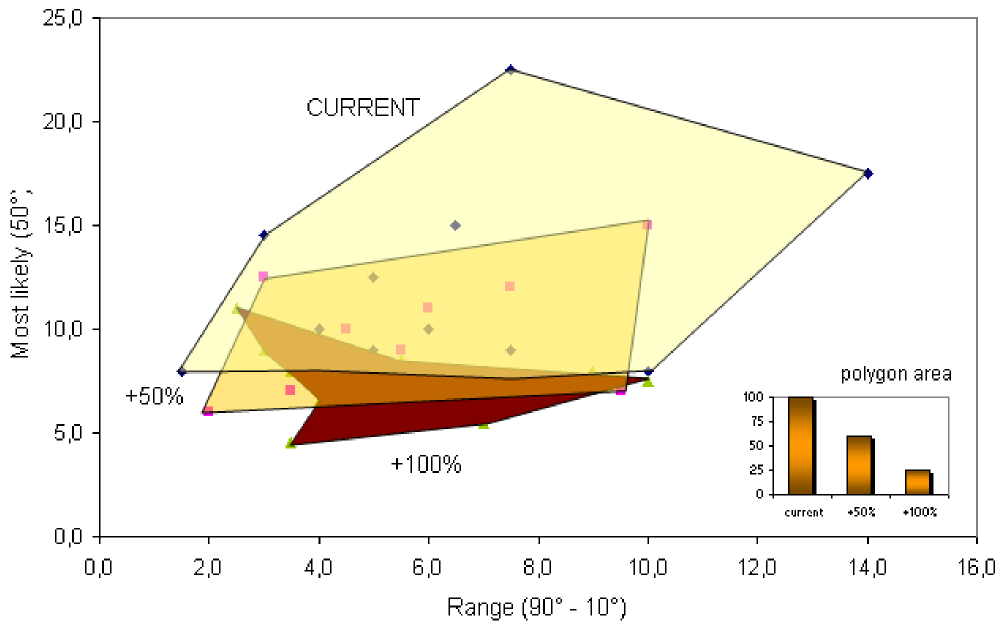


Figure 8: Direct ordination of the experts' estimation of the three RD&D funding scenarios based on the range between the 90th and 10th percentile and the most likely value (50th percentile) of electricity cost produced with solar technologies in 2030. The outermost limits of each scenario were connected to

enclose the points of each scenario in a polygon, whose areas are reported in the histogram in the lower right part of the graph (area of current funding scenario=100). [Light yellow poligon: current funding; Orange poligon: +50%; Dark red poligon: +100%].

3. Diffusion of solar technology

In the fourth section of the questionnaire, the first question the experts had to answer was to indicate which geographical area of the world had the highest probability of being the first to reach commercial success (Figure 9).

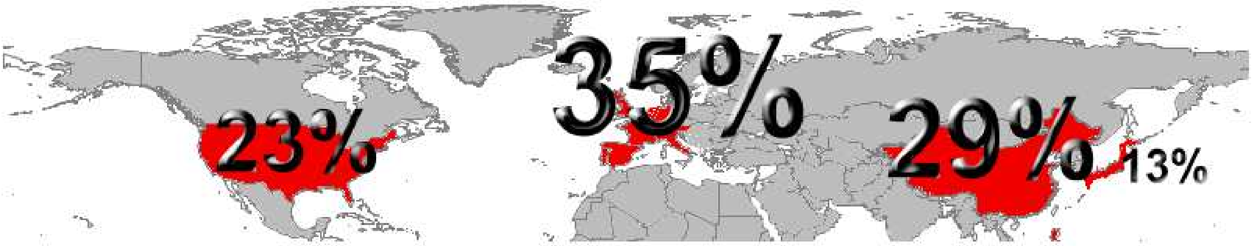


Figure 9: Countries' probability of being the first to reach commercial breakthrough in solar technology.

The first area to reach the breakthrough in solar technologies seems more likely to be, according to the experts' assessment, the EU, followed with decreasing probability by China, United States and Japan. This statement could have been slightly biased by the fact that it was indicated by European experts. It's nevertheless true that it represents a new emerging perspective which takes into account the latest advancements in research, but also the capacity to implement the development and deployment phases which would lead solar technologies to commercial success.

Then the experts considered how the dynamics of technology transfer between countries and regions of the world could affect the choice to support internal R&D programs. The majority of the experts (81%) affirmed that the current conditions reflect a relatively successful cooperation among different countries, which results in important knowledge spillovers. However, they agreed on the binding need for each country to invest in its own R&D program in order to develop absorptive capacity and therefore to be ready to adopt breakthrough technologies developed by other countries.

The analysis was not limited to the assessment of positive knowledge spillovers, but considered the potential negative externalities on the environment and society as a whole which might derive from the diffusion of solar technologies. According to the experts, the large scale deployment of PV technology could cause problems of land use and soil occupation, henceforth calling for a careful definition of the site and the design of the facility. Another important concern is the use of toxic components (eg. CdTe toxicity), although experts refer that industries in the PV sector are advanced in the management and recycling of toxic substances. In particular, recycling is central for the development of integrated business, and needs to be developed and applied to reduce the negative impact associated with the life cycle of PV modules.
The extensive implementation of CSP infrastructures would instead raise issues for their visual impact and local environmental effects. Moreover, the use of water might be a limit, and a possible solution to this issue would be the development of dry cooling.

The last section of the questionnaire assessed the crucial role of market diffusion for the success of PV and CSP technologies and their competitiveness with fossil fuel energy technologies.

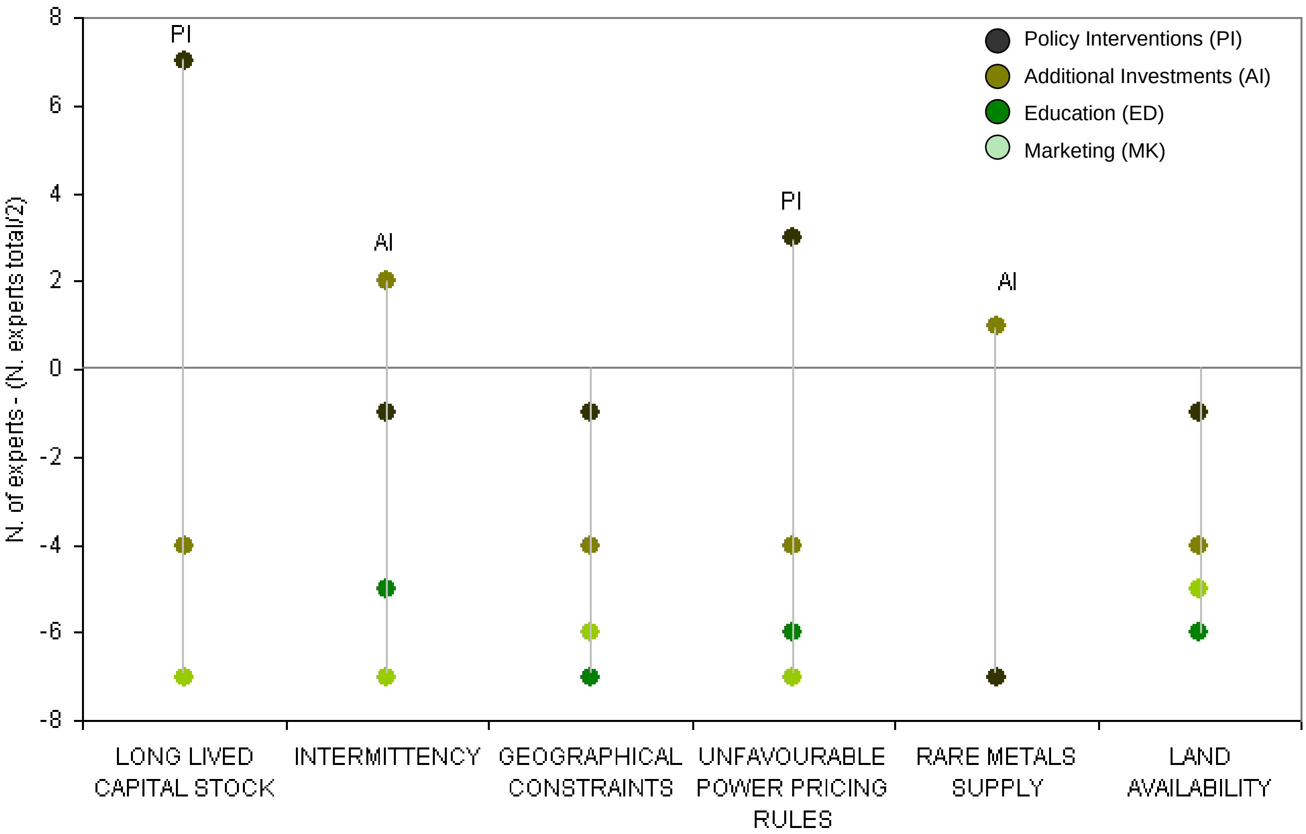


Figure 10: Factors which could represent non-technical barriers to the diffusion of solar technologies and potential solutions to overcome the barriers. In the graph, the line corresponding to the zero value of the y axis distinguishes the solutions associated with each single barrier in two groups: the first group corresponds to the solutions which have been considered by the experts as important to overcome the barrier, while the second (lower) group is composed by the solutions which collected fewer votes by the experts.

According to the evaluation of the experts, four barriers in particular could set back the diffusion of solar technologies (Figure 10).

First of all, the investments in capital made in the past make it hard to switch to a new technology unless the capital is worn out and has to be replaced. Therefore the presence of long-lived capital stock is one of the main barriers to the diffusion of solar technologies in the market, unless policy intervention is directed to accelerate capital turnover. The second barrier recognized by the experts is linked to unfavourable power pricing rules, as renewable energy sources feeding into an electric power grid do not receive full credit for the value of their power. As expected, policy intervention is almost univocally recognized as the solution. The provision of rare metals for some specific PV and CSP infrastructures represents the third possible limit to the diffusion of solar technologies, while the fourth recognized barrier is intermittency in the supply of solar power and therefore to the need of adequate storage systems. According to most experts, both issues can be mainly solved through additional investments. Some experts also consider land availability as well as other geographical constraints (e.g., sun irradiation), although the relative importance of these barriers is low, compared to the previous ones.

Once the experts had reasoned about the non-technical barriers to market diffusion, we asked them to assume that in 2030 solar technologies would be technically ready to compete with conventional fossil fuels. They provided their estimate on the diffusion trend of solar technologies in the power generation mix (Figure 11), by reporting probabilities associated to three possible scenarios where solar technologies represent 5, 20 and 30% of the power mix for three groups of countries.

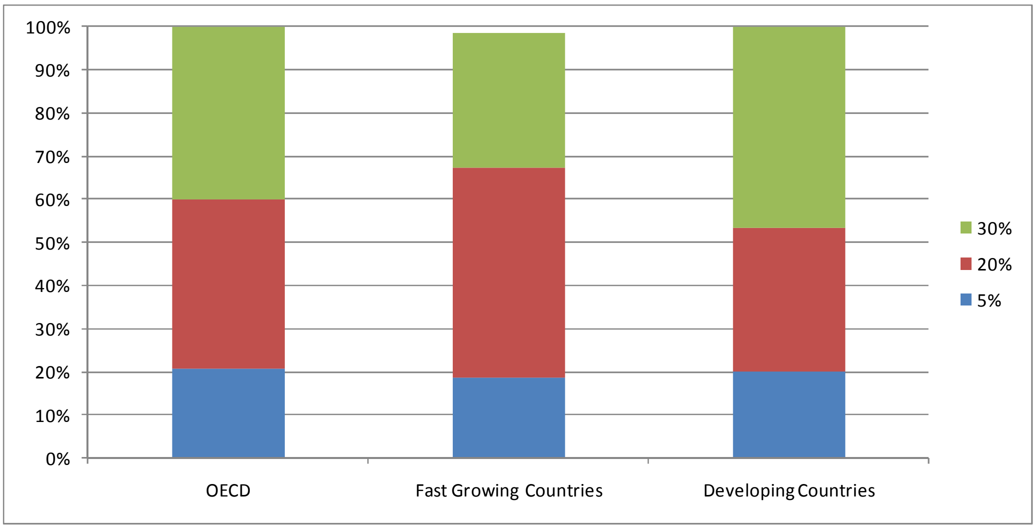


Figure 11: Penetration rates of solar technology in the power generation mix in 2050

According to the experts' answers, OECD countries will have almost the same probability to experience a penetration of solar technology into the power generation mix of 20% and of 30%.
In Fast Growing countries (BRICS) the trend of adoption of solar technologies would instead show a higher probability of being limited to 20%.

Several experts affirmed that solar technologies could experience a higher penetration rate (30%) in developing countries, since they would not have to overcome problems of substitution of existing power infrastructures ("long-lived capital stock" and "lock-in effect"). The diffusion of solar technologies in developing countries would help to overcome the issue of reaching and electrifying remote areas (eg in Africa). The experts also thought that developing countries will not have to face problems with transfer of knowledge.

Most of the experts specified that the ceiling to the diffusion trend of solar technologies will not, in any case, exceed 50% of total power generation. This limit will be caused by technical issues, such as the need for electricity storage and management of variable power with the compensation of intermittency and resource and land availability. Effective solutions to those problems would require significant investments and are not likely to be found before 2050.