FONDAZIONE ENI ENRICO MATTEI

NOTA DI LAVORO

1.2012

The Future Prospect of PV and CSP Solar Technologies: An Expert Elicitation Survey

By **Valentina Bosetti**, Fondazione Eni Enrico Mattei and CMCC, Italy

Michela Catenacci, Fondazione Eni Enrico Mattei, Italy

Giulia Fiorese, Fondazione Eni Enrico Mattei and Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy

Elena Verdolini, Fondazione Eni Enrico Mattei and CMCC, Italy

Climate Change and Sustainable Development Series
Editor: Carlo Carraro

The Future Prospect of PV and CSP Solar Technologies: An Expert Elicitation Survey

By Valentina Bosetti, Fondazione Eni Enrico Mattei and CMCC, Italy
Michela Catenacci, Fondazione Eni Enrico Mattei, Italy
Giulia Fiorese, Fondazione Eni Enrico Mattei and Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy
Elena Verdolini, Fondazione Eni Enrico Mattei and CMCC, Italy

Summary

In this paper we present and discuss the results of an expert elicitation survey on solar technologies. Sixteen leading European experts from the academic world, the private sector and international institutions took part in this expert elicitation survey on Photovoltaic (PV) and Concentrated Solar Power (CSP) technologies. The survey collected probabilistic information on (1) how Research, Development and Demonstration (RD&D) investments will impact the future costs of solar technologies and (2) the potential for solar technology deployment both in OECD and non-OECD countries. Understanding the technological progress and the potential of solar PV and CPS technologies is crucial to draft appropriate energy policies. The results presented in this paper are thus relevant for the policy making process and can be used as better input data in integrated assessment and energy models.

Keywords: Expert Elicitation, Research, Development and Demonstration, Solar Technologies

JEL Classification: Q42, Q55

The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n° 240895 – project ICARUS "Innovation for Climate Change Mitigation: a Study of energy R&D, its Uncertain Effectiveness and Spillovers". We would like to thank the participating experts listed in Table 1 and M. Bogana (Fondazione Politecnico di Milano), G. Manzolini and P. Silva (Politecnico di Milano), who helped with the pilot tests. We are also grateful to Laura Diaz Anadon, Stergios Athanassoglou, Inês Lima Azevedo, Erin Baker, Thomas Longden, Granger Morgan and the other participants to the Carnegie Mellon CEDM/CDMC seminar series for their suggestions.

Address for correspondence:

Valentina Bosetti
Fondazione Eni Enrico Mattei
Corso Magenta 63
20123 Milan
Italy
Phone: +390252036948
Fax: +3902520336946
E-mail: valentina.bosetti@feem.it

The Future Prospect of PV and CSP solar technologies: An Expert Elicitation Survey

Valentina Bosetti [1,2,*], Michela Catenacci [1], Giulia Fiorese [1,3] and Elena Verdolini [1,2]

[1] FEEM - Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123 Milano, Italy
[2] CMCC - Centro Euro-Mediterraneo per i Cambiamenti Climatici
[3] Dipartimento di Elettronica e Informazione, Politecnico di Milano, Via Ponzio 34/5, 20133 Milano, Italy

e-mails: valentina.bosetti@feem.it; michela.catenacci@feem.it; giulia.fiorese@feem.it; elena.verdolini@feem.it

* Corresponding author. Fondazione Eni Enrico Mattei (FEEM), C.so Magenta 63, 20123 Milan, Italy. Tel.: +39-02-5203-6948; Fax: +39-02-5203-36946.

The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement n° 240895 – project ICARUS "Innovation for Climate Change Mitigation: a Study of energy R&D, its Uncertain Effectiveness and Spillovers".We would like to thank the participating experts listed in Table 1 and M. Bogana (Fondazione Politecnico di Milano), G. Manzolini and P. Silva (Politecnico di Milano), who helped with the pilot tests. We are also grateful to Laura Diaz Anadon, Stergios Athanassoglou, Inês Lima Azevedo, Erin Baker, Thomas Longden, Granger Morgan and the other participants to the Carnegie Mellon CEDM/CDMC seminar series for their suggestions.

Abstract: In this paper we present and discuss the results of an expert elicitation survey on solar technologies. Sixteen leading European experts from the academic world, the private sector and international institutions took part in this expert elicitation survey on Photovoltaic PV) and Concentrated Solar Power (CSP) technologies. The survey collected probabilistic information on (1) how Research, Development and Demonstration (RD&D) investments will impact the future costs of solar technologies and (2) the potential for solar technology deployment both in OECD and non-OECD countries. Understanding the technological progress and the potential of solar PV and CPS technologies is crucial to draft appropriate energy policies. The results presented in this paper are thus relevant for the policy making process and can be used as better input data in integrated assessment and energy models.

Keywords: expert elicitation; research, development and demonstration; solar technologies.

1. Introduction

Solar Photovoltaic (PV) and Concentrated Solar Power (CSP) represent promising options for electricity production and could significantly contribute to lowering CO_2 emissions from fossil fuel use. Their potential as carbon-free energy carriers in Europe is clearly demonstrated by their inclusion in the Strategic Energy Technology (SET) Plan set out by the European Commission (EC) in 2008, The SET Plan provides a framework to accelerate the development and deployment of cost-effective low carbon technologies.[1] PV and CSP are among nine "technological paths"[2] which the EU and its member states plan to apply to collectively promote sustainable energy use (EC, 2009). Since 2010, the large-scale demonstration of solar technologies is supported and coordinated through the Solar Europe Initiative.

EU commitment to solar technologies has been strong. In 2007, solar PV and CSP represented 30% of public Research and Development (R&D) investments in the EU, reaching around 209 million euros. Collectively, EU public R&D investment in 2007 was higher than public support in the USA (EC, 2009 and IEA, 2011). The highest public investments for PV came from Germany and France, while Italy and Spain led the investment in CSP. Notwithstanding this predominant role, the environmental and economic challenges associated with the energy sector and the renewed attention given to solar technologies in the political debate led Europe to call for major commitment to support solar technologies and their deployment with further RD&D investment. As a result of the 2009 stimulus packages, solar EU RD&D public spending increased by 30%.

The contribution of solar electricity to renewable energy supply in the EU is still marginal, but growing at an impressive rate. 29 GW generation capacity in the EU accounted for around 70% of the total world-wide of PV electricity production at the end of 2010, but represented a mere 2% of total renewable energy generation in the EU[3]. However, PV accounted for 13.5 GW of the 56.3 GW new capacity installed in the EU in 2010 and was second only to gas-fired electricity production. PV cumulative installed capacity thus increased by more than 80%, 10 times higher than the predicted target for 2010 (Jäger-Waldau et al., 2011). From now to 2020, the European Photovoltaic Industry Association foresees annual growth rates as high as 36%.[4]

With respect to CSP capacity, additional 898 MW are currently under construction and another 842 MW have already registered for feed-in tariff schemes. If all these projects are implemented successfully, by 2013 total capacity will reach 2.5 GW (Jäger-Waldau et al., 2011). According to the European Solar Thermal Electricity Association (ESTELA), 30 GW of CSP capacity could be installed

[1] The EU's Climate Change Package, adopted in 2008, aims to ensure that the EU will achieve its emission targets by 2020: a 20% reduction in greenhouse gas emissions, a 20% improvement in energy efficiency, and a 20% share of renewables in the EU energy mix (EC, 2009).

[2] The SET technologies selected by the EU are: wind energy, photovoltaics (PV) and concentrating solar power (CSP), carbon dioxide capture and storage (CCS), biofuels, hydrogen and fuel cells, smart grids, nuclear fission (with a focus on generation IV reactors), and nuclear fusion (EC, 2009).

[3] In the USA, PV represents 0.2% of renewable energy production. CSP accounts for an even smaller share of renewable energy: 0.05% in EU countries (namely, 730 MW installed capacity in Spain) and 0.04% in the United States (Jäger-Waldau et al., 2011) in 2010.

[4] The potential of solar technologies is testified by similar trends around the world. World PV electricity production increased almost by two orders of magnitude since 2000, with annual growth rates between 40% and 90%. The most rapid growth over the last five years was observed in Asia, where China and Taiwan together account for almost 60% of world-wide electricity production. In 2010 PV cell production was around 24.1 GW, representing a doubling of production compared to 2009 levels (Jäger-Waldau et al., 2011 and Arzivu et al., 2011).

in Europe, providing around 100 TWh in 2020. The EU Solar Industry Initiative itself aims for a cumulative installed CSP capacity of 30 GW in Europe, out of which 19 GW would be in Spain. These high growth projections continue in spite of the recent economic crisis.

Over the last 20 years, solar technologies have shown impressive cost reductions and have benefited from support schemes reducing the wedge between solar and conventional electricity costs. PV generation costs decreased from 22 USD/Wp in 1980 to about 2-5 USD/Wp in 2005. This was mainly due to increases in plant size (economies of scale), improvements in module efficiency, and reductions in the cost of silicon. In these respects, R&D investments played a crucial role (Nemet, 2006). Support schemes for solar technologies aim at favoring deployment even though production costs are not competitive with traditional fossil electricity production. The Green Fund included in the economic stimulus packages of 2010 for the EU member states and Norway totalled 54.2 billion USD, of which around 3.5 were devoted to low carbon renewable energy (Robins et al, 2009). In addition, a number of countries implement feed-in-tariffs and other forms of support to small and large scale solar technology deployment as well as targeted tax-breaks.

Without support schemes, solar electricity generation costs are still higher than competing technologies. This wedge is big enough that a mild carbon price, in the order of 10-20 $ per ton CO2, would not necessary tilt the picture. CSP costs are even higher, with investment costs for Parabolic Trough systems around 3.15-4.20 USD/W, which rise to 4.90 USD/W if the system includes six-hour thermal storage (Denholm et al., 2010; Price et al., 2002). In addition to higher production and investment costs, solar power also presents a number of additional challenges linked with the need to upgrade the electricity grid (to allow for dispersed production and for the transport of electricity for long distances) and with system integration (to balance off intermittency). Without these improvements, solar technologies deployment will not be successful.

Government fiscal support so far has been substantial, and a renewed commitment is required to support widespread deployment: significant RD&D investments will be necessary to foster technological improvements, to promote learning-by-doing effects and economies of scale (Jäger-Waldau et al., 2011). Given the high opportunity costs involved in these decisions, it is thus mandatory to understand how these technologies will improve and how costs will evolve over time. Such insights would be extremely valuable for policy makers, who clearly need to strike a balance between competing technological options. A better assessment of future uncertainties will definitely help in drafting sound policies.

Our research provides a number of important contributions in this respect. We develop an *ad hoc* expert elicitation protocol to gain a deeper understanding of the current status and future developments in solar technologies. We investigate cost-competitiveness by collecting probabilistic information on the solar technologies expected cost by experts. We devote particular attention to how cost reductions could be affected by EU public RD&D programs[5]. With respect to previous literature, we enlarge the focus of research by (1) providing the first elicitation of European experts on the future potential of energy technologies, (2) assessing both PV and CSP technologies, (3) considering cost

[5] Public RD&D investments are only a fraction of the RD&D effort in any given country, but there is little available evidence on private RD&D investments in renewable technologies. A recent analysis estimates that private contributions represent around 60% of the total RD&D investments in PV and CSP technologies in 2007 (EC, 2009). The little available evidence also shows that private investments are expanding rapidly. In particular, solar energy surpassed all clean energy technologies in terms of venture capital investments in 2008, with an investment of 5.45 billion USD and an 88% growth from 2007 (Bloomberg, 2009).

reductions both in the EU and in other relevant regions of the world, (4) assessing potential non-technical barriers to diffusion and deployment of solar technologies which would have to be addressed even if costs of production were lower.

This paper is organized as follows: Section 2 comments on how expert judgment elicitation can be used to inform policy makers and presents the expert elicitation protocol designed for this study. Section 3 presents the experts' estimates of future costs under different RD&D funding scenarios and Section 4 discusses experts' assessment concerning technology deployment. Section 5 concludes summarizing and commenting on main results from the survey. These are relevant both for their policy implications and for their potential to increase the reliability and the quality of projections from integrated assessment and energy models.

2. The Elicitation Protocol

The objective of our survey is to assess the future technical developments and costs of six families of technologies for solar electricity production. We focus on Crystalline-silicon Photovoltaic (PV), Thin-film PV, Concentrating PV, Organic PV, Third Generation PV and Concentrated Solar Power (CSP) (Figure 1). These technologies were chosen because they are at different level of development, but even for the most mature ones, such as Crystalline-silicon PV, there is a strong need for further research and technical improvements (Ginley et al., 2008).

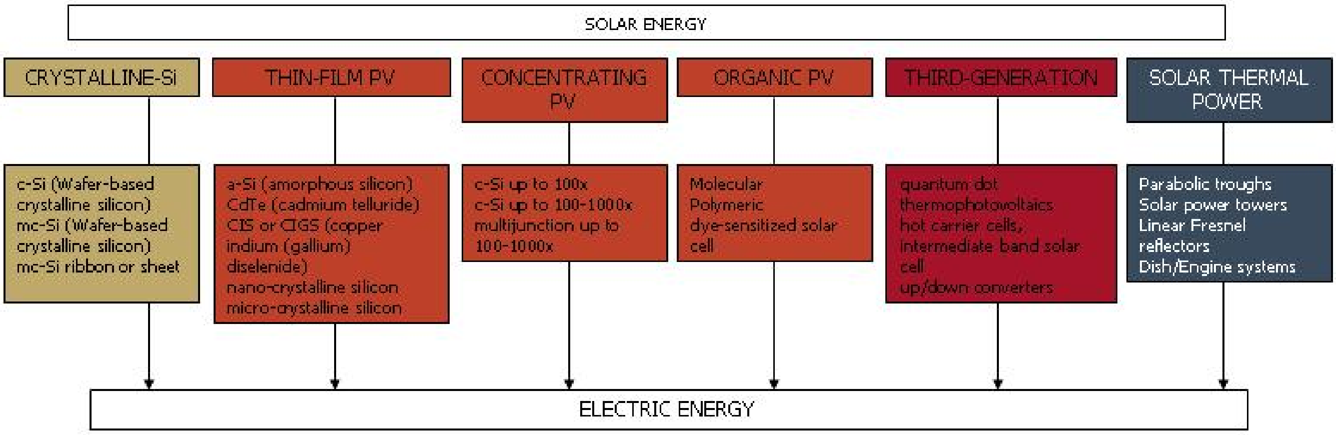

Figure 1. Solar technologies considered in the interviews with the experts.

We surveyed experts to collect judgements on the future costs of these technologies, how these will be affected by EU public RD&D programs, and what non-technical barriers could prevent their diffusion. The questionnaire was divided into five sections (for the full version of the questionnaire, refer to Bosetti et al., 2011):

1. Reference data on solar technologies, *current cost estimates* and current RD&D investments for PV and CSP technologies;
2. Identification of *existing technical barriers* preventing the success of solar technologies and of the type of RD&D investment necessary to overcome them;
3. *Optimal allocation of public EU RD&D* funding across different technology options;

4. *Estimates of the costs of solar electricity in 2030* and how they might be affected by different RD&D programs;
5. *Potential for solar technology diffusion*, the role of technology transfer dynamics and non-technical barriers.

Expert judgments are the expressions of informed opinion that experts make based on their knowledge and experience with respect to technical problems (Hogarth 1987, Morgan and Henrion 1990, Cooke, 1991). Eliciting experts' judgements means gathering subjective probabilities that a specific event will take place in the future through specifically designed methods of verbal or written communication. The outcome of an expert judgement elicitation is probabilistic information on future states of the world. Experts' judgements are particularly useful and are often required in probabilistic decision making and in the evaluation of risks. These techniques are increasingly applied to different research fields when dealing with complex phenomena characterized by uncertainty and lack of data.

The use of expert judgement elicitation has been applied in the past to inform policy-makers. An important example is represented by the uncertainty study of accident consequence codes for nuclear power plants jointly undertook by the European Commission and the United States Nuclear Regulatory Commission during the years 1990 – 1999 (Cooke et al., 1999).

Gathering experts' judgement requires a sound elicitation protocol. Since the seminal work by Tversky and Kahneman (1974), a growing body of literature has substantiated our knowledge on heuristics and biases which affect judgments under uncertainty. In spite of their deep and recognized knowledge of the subject, experts can be subject to the same cognitive and motivational biases as all human beings, unless certain preventive measures are used in the elicitation. Such 'biases' range from the skewing of the experts' estimate around a reference point (anchor), to the heuristic that makes us value as less risky those technologies we deem as more beneficial, to overconfidence biases.

Protocols and techniques have been defined to minimize such biases (Clemen and Reilly, 2001; Keeney and von Winterfeldt, 1991; Meyer and Booker, 1991; Morgan and Henrion, 1990; O'Hagan et al., 2006; Phillips, 1999; Walls and Quigley, 2001). Our elicitation protocol builds upon this vast literature on decision analysis and expert judgment elicitation. Some crucial features that should be carefully included in a robust elicitation process are: carrying out the survey in person, defining the metrics and the object of the elicitation process as accurately as possible, warning the experts about main biases and heuristics and training them to the elicitation exercise, avoiding anchoring numbers and using tools to represent uncertainty that facilitate its quantification.

We carefully addressed each of these issues while designing our protocol. We specifically made the choice of interviewing our experts face-to-face. We started each interview with a warm-up phase designed to brief experts on sources of biases and difficulties in assessing probabilities. Subsequently, we asked them to carefully assess the current status and cost of solar technologies and all potential barriers. This part of the survey aimed at "tuning in" the experts and avoiding the possibility of overlooking or exaggerating problems. Moreover, we put specific emphasis on each different cost component and ask the expert to carefully consider the combination of events which would lead to cost improvements.

All these precautions were put in place to avoid an overestimation on the part of the experts regarding the likelihood that solar energy costs would decrease in the future. In addition, as we will explain more in detail below, the key question in the survey on the future costs of solar technologies was asked using two different formats to test for possible sources of bias, such as overconfidence and anchoring effects. Although biases cannot be entirely eliminated the structure of the protocol we developed ensures their minimization.

The choice of experts to be involved in the elicitation exercise is as important as the design of the survey itself. The success of the elicitation crucially depends on the expertise, the technical background and the personality of each expert, as well as on her ability to provide probabilistic judgments (O'Hagan et al., 2006). We gathered a mix of respondents with strong scientific backgrounds and sound empirical knowledge. Our careful selection resulted in a balanced group of experts who represent the major perspectives and fields of knowledge (engineers, economists, and policy makers) but with heterogeneous backgrounds. Academia, institutions and the private sector are represented in a balanced way to ensure a thorough analysis of both basic and applied research issues as well as policy implications. The experts that participated in the survey are listed in Table 1. All answers are anonymously reported in the rest of the paper.

Table 1. List of experts participating in the survey.

Name	Affiliation	Country
Rob Bland	McKinsey	USA
Luisa F. Cabeza	University of Lleida	Spain
Roberta Campesato	Centro Elettrotecnico Sperimentale Italiano	Italy
Carlos del Canizo Nadal	Universidad Politecnica de Madrid	Spain
Aldo Di Carlo	UniRoma2	Italy
Ferrazza Francesca	Ente Nazionale Idrocarburi	Italy
Paolo Frankl	International Energy Agency	UK
Arnulf Jäger-Waldau	European Commission DG JRC	Germany
Roland Langfeld	Schott AG.	Germany
Ole Langniss	FICHTNER GmbH & Co. KG	Germany
Antonio Luque	Universidad Politecnica de Madrid	Spain
Paolo Martini	Archimede Solar Energy	Italy
Christoph Richter	German Aerospace Center	Germany
Wim Sinke	Energy Research Centre	The Netherlands
Rolf Wüstenhagen	University of St. Gallen	Switzerland
Paul Wyers	Energy Research Centre	The Netherlands

At the beginning of our survey, experts were asked to self-assess their level of expertise on a scale from 1 to 5 with respect to the 6 families of technologies included in the survey. This step is fundamental because it provides insights on the possible biases in experts' responses, which can be dictated by their preference or better knowledge of a specific technology among the ones surveyed. Figure 2 and Figure 3 show the results of the self-assessment exercise and provide some descriptives regarding our pool of experts. Figure 2 plots the experts' distribution with respect to two indexes. The specialization index (y-axis) represents the share of technologies in which the expert did not attribute herself a top score (the higher this index, the more specialized the expert is in only few technologies). The coverage index (x-axis) represents the share of technologies in which the expert attributed herself at least a "medium" level expertise (corresponding to a self-assessment of at least 3). Most experts have a high degree of specialization (Specialization Index > 50%), meaning that they attributed themselves the highest score in less than 50% of the selected technologies. Conversely, the greater spread along the X axis suggests heterogeneous levels of knowledge with respect to the different solar technologies (Coverage Index): six out of seventeen experts score themselves as having "average" knowledge on less than 50% of the selected technologies. Experts' background partially influences both specialization and coverage: all the experts from the private sector are highly specialized, three out of five experts from the international institutions show high coverage of solar technologies knowledge (Coverage Index >50%).

Figure 3 shows expertise levels by technologies. A higher proportion of experts in relatively more mature technologies, such as Crystalline-silicon, self assess as having "high expertise". The contrary is true for more innovative technologies, such as 3rd Generation PV. Moreover, most experts with a diverse background declared a high level of expertise on relatively mature solar technologies, such as Crystalline-silicon PV and CSP. The experts with a good knowledge on innovative technologies, such as Third Generation PV and Organic PV, were mainly academics.

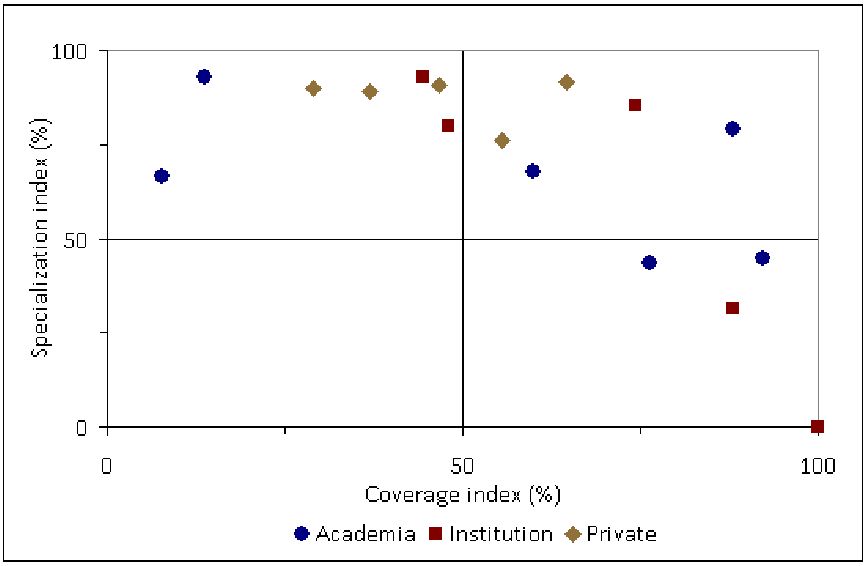

Figure 2: Ordering of the experts based on the Coverage Index and the Specialisation Index

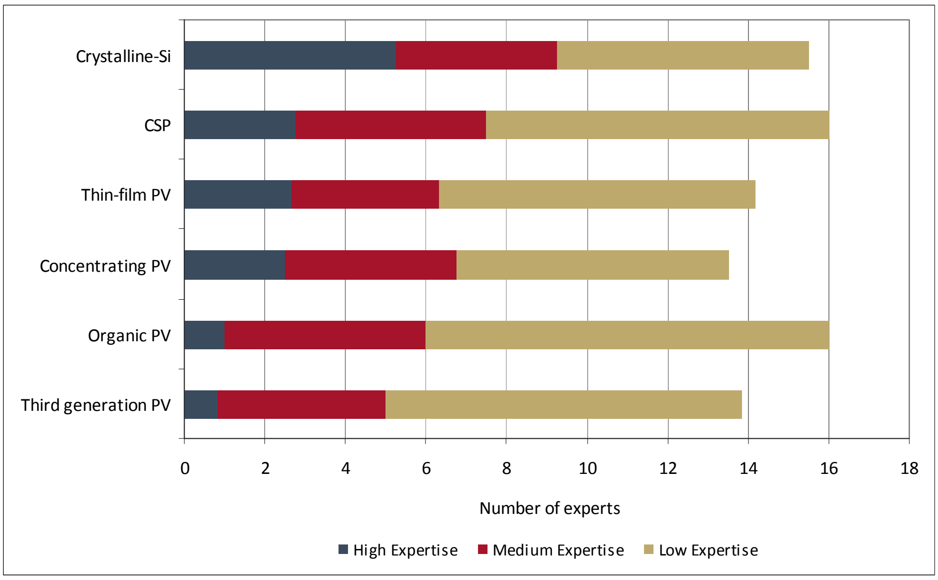

Figure 3: Distribution of the experts with respect to six major classes of solar technologies

In a 1-5 scoring system, high expertise >3; medium expertise =3; Low expertise <3.

Our analysis contains a number of important innovative elements. First, we provide the first elicitation of European experts on the future potential of energy technologies. Expert elicitation has been widely used in the USA to gather probabilistic information on the potential success of carbon-free energy technologies (e.g., Baker et al., 2009a, 2009b; Baker and Keisler, 2011; Curtright et al., 2008; Chan et al., 2011), but so far it has not been carried out in Europe. Interviewing EU experts represents a crucial contribution to predicting solar technologies developments given that Europe is a leading country area in terms of installed photovoltaic capacity.

Second, we broaden the research horizons by focusing on the development and diffusion of solar technologies in Europe and worldwide. Previous studies focused entirely on the USA (e.g., Baker et al., 2009a; Curtright et al., 2008), thus ignoring important players in the innovation process and relevant markets for the deployment of these technologies. Enlarging the focus of the analysis to include fast developing and developing countries, like China and India, is relevant given their market potential.

Third, unlike previous studies (Baker et al., 2009a; Curtright et al., 2008), we assess the evolution of both PV and CSP technologies. Considering future developments and costs of both these technological options is necessary due to their inherent differences: PV technologies are currently more developed and closer to being cost-competitive to traditional fossil generation than CSP technologies. However, CSP has high production potential and cost reductions could make it a very attractive technology.

Finally, we also investigate the non-technical conditions that could set back the diffusion of solar technologies worldwide. Non-technical barriers could hinder deployment even if competitiveness on a cost basis were achieved. Important issues to consider include the upgrade of the electricity grid to support dispersed electricity production in the case (PV), or the efficient dispatch of electricity across large distances (CSP).

Surveys were carried out between May and October 2010. A follow up of the interviews allowed us to check the elicited information, to deepen the discussion with each of the experts, and, when necessary, to correct for possible inconsistencies. More information on the pool of experts and on their expertise with respect to the analyzed technologies are provided, together with the whole survey, in Bosetti et al. (2011).

3. Future costs under different RD&D funding scenarios

To identify the drivers and bottlenecks affecting PV and CSP costs, the survey asked each expert to comment on the current level of technical development of the proposed technological options, to elaborate on current costs and to think of avenues of improvement. This introductory phase also responded to the methodological need to “tune in” the experts and provide them with a common background on EU and global RD&D funding, as well as on solar technology markets. Such a step was particularly relevant in our case since the experts we interviewed are from different EU countries and are operating within fairly diverse national research frameworks.

Subsequently, experts were asked to identify the main bottlenecks to cost reductions and to specify what type of RD&D would be mostly needed. Table 2 reports keywords that were mentioned by at least four experts when discussing barriers and issues linked to each of the technological options. In particular, Organic PV attracted very diverse comments and consensus among experts on what the problems are and what solutions are needed.

Table 2. Technical barriers to the development of the technology: keywords mentioned by at least 4 experts.

Crystalline-silicon PV	***Thin-film PV***	***Concentrating PV***	***Organic PV***	***Third generation PV***	***CSP***
Efficiency, materials	Efficiency, stability, toxicity, durability	Stability, complexity, very high costs	Efficiency stability, lifetime	Efficiency, proof of concept	Heat storage, durability, material

Each expert was asked to indicate what would be the optimal distribution of the current RD&D budget between the different technologies, keeping in mind the discussion on current status and the main barriers to cost reduction previously identified. Each expert was given 100 "chips" to distribute across the 6 technological paths. Each chip represented around 1.63 million UDS, for a total budget of 163 million USD.[6] The budget allocation of each expert is provided in Figure 4.

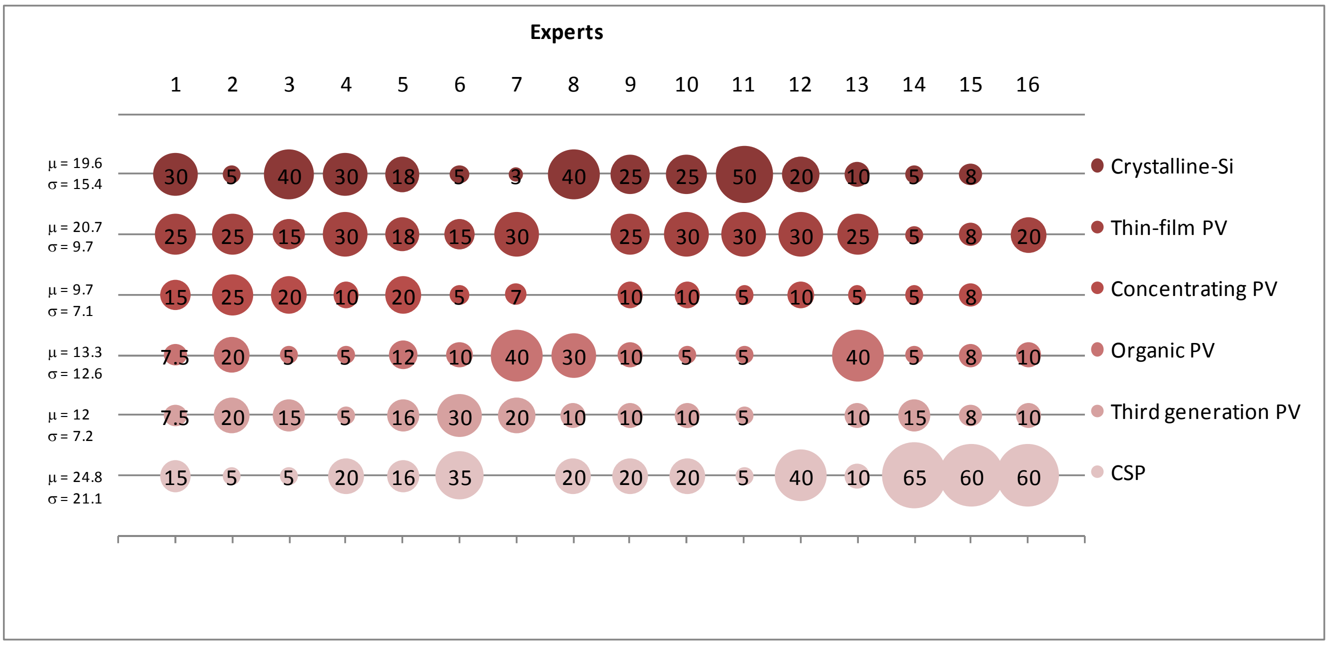

Figure 4. Experts' optimal distribution of RD&D budget across technologies. The total budget of each expert is 100 chips and each chip represents approximately 1.63 million USD. Each bubble represents the number of chips an expert allocated to each technology. For each row (technology) we report the mean and variance of allocations.

Seven (nine) out of sixteen experts suggested that at least a quarter of the budget in the next twenty years be allocated to improving more mature technologies such as Crystalline-silicon PV (Thin-film PV). On the one hand, experts show consensus on allocating a relatively large part of the budget (on average more than 20 chips) to what is considered a promising and relatively stable technology such as Thin-film PV. On the other hand, other relatively more advanced technologies such as Crystalline-

[6] The public EU yearly budget from 1980 to 2009 (IEA 2011)

silicon PV and CSP received similar or greater shares of the total budget on average, but with much wider variability across experts, indicating less consensus. In the case of Crystalline-silicon PV and CSP, the shares allocated by the experts largely reflect the area of expertise, while this is not the cases for the other technologies.[7]

Notwithstanding the commitment to improve mature technologies, most experts chose to diversify their portfolio of investments by allocating some of their budget to each of the technological options. A fairly uniform low amount of chips was allocated to Concentrating PV and Third Generation PV (on average around 10 chips or roughly 16 million USD), suggesting that it is important to identify their true market potential. Organic PV is more controversial: it received on average a larger amount of chips (13.3) but with high fluctuations across experts, reflecting heterogeneity of views.

When investigating the type of government funding experts have in mind, we find that applied R&D and Demonstration should take the largest share (in average more than 70%) for Crystalline-silicon PV, Thin-film PV and CSP (see Figure 5).

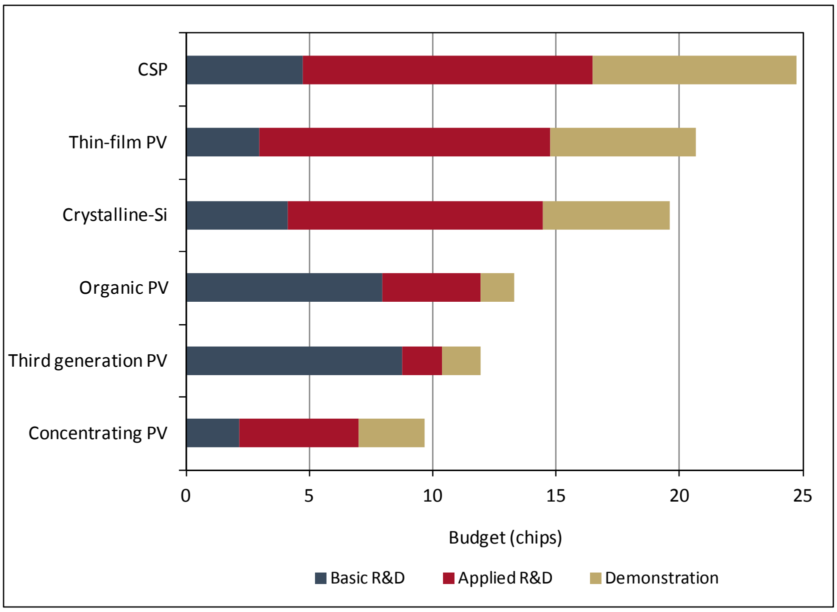

Figure 5. Type of RD&D funding across different technologies, aggregated over all experts.

While experts indicated that third generation and organic solar should receive a relatively larger share of basic research funding, they also indicated the need to work "out of the lab" to test efficiency, to improve lifetime and to bring down costs via learning-by-doing processes. Experts explicitly indicating that funding for Demonstration (as opposed to basic Research and Development) should be a consistent and crucial part of public investment. This is in contrast with the EU's institutional choice of allocating most of the public RD&D budget to Research and Development. In 2007, for example, only 11% (3%) of public spending for PV and CSP went to demonstration activities (EC, 2009).

In the contest of the fast evolution of solar technologies, the main driving force behind our analysis was the need to evaluate the RD&D investment impact on their future cost. The core of the survey was therefore meant to gather information from each expert on the expected cost of electricity produced with solar technologies in 2030. We asked each expert to provide estimates following a discussion on

[7] See Bosetti et al. (2011) for a detailed discussion on the correlation between area of expertise and responses to the survey.

main assumptions that might affect costs, such as efficiency, plant investment, operating costs, lifetime, peak insolation power and discount rate.[8]

Those estimates were conditional on different scenarios of EU public funding for RD&D, with investments being evenly spread over the years.[9] We considered three scenarios: the "Current RD&D" scenario assumed that annual EU public RD&D would be 163 million of USD through 2030. The "+50% RD&D" scenario assumed a 50% increase of public EU RD&D investment sustained until 2030 (corresponding to about 245 million USD/year). Finally, the "+100% RD&D" assumed that the annual public EU RD&D would scale up to twice the current levels (corresponding to 326 million USD/year).

Experts were explicitly asked to consider that the only variable changing across scenarios was public EU funding, while private funding as well as other countries RD&D programs would remain the same across scenarios. Moreover, we specifically asked them to assume that no incentive or subsidy such as feed-in tariffs or renewable standards would be in place.

To control for cognitive heuristics (such as those discussed in the previous section) we first asked to provide the 10^{th}, 50^{th} and 90^{th} percentile of costs estimates. We then checked the consistency of responses by asking each expert to estimate the probability that in the three funding scenarios mentioned above the cost of solar electricity in 2030 would be lower than 11.27, 5.55 or 3 cUSD/kWh.[10] This essentially meant asking the same questions to the expert twice, but with different "focus": the first time they were asked to provide cost estimates, the second to provide probability estimates.[11] Experts' estimates of the expected cost of electricity in 2030 are reported in Figure 6.

[8] A spreadsheet to compute electricity costs given alternative assumptions about key technical characteristics was made available to the experts to help them reason in terms of technical endpoints if they preferred (Bosetti et al., 2011).

[9] This assumption was made even though there have been significant oscillations experienced by EU countries in the last 20 years (IEA, 2011).

[10] The three different "breakthrough" cost levels considered when asking the second question correspond to projections of the costs of electricity from fossil fuels or nuclear in 2030. The first breakthrough cost (11.27 cUSD/kWh) corresponds to the 2030 projected cost of electricity from traditional coal power plants in the presence of a specific policy to control CO2 emissions (thus effectively increasing electricity costs from fossil sources). Specifically, we assumed a carbon price accounting for more than half of the cost of electricity (5.8 cUSD/kWh), which is in line with a 550ppm CO2 only stabilization target by 2100 (according to projection of the WITCH model in Bosetti et al, 2009). The second breakthrough cost (5.55 cUSD/kWh) is the projected cost of electricity from traditional fossil fuels in 2030, without considering any carbon tax. Finally, the third breakthrough cost (3 cUSD/kWh) assumes that solar power might become competitive with the levelized cost of electricity from nuclear power.

[11] Fourteen out of the sixteen experts showed some inconsistency across the two elicitation methods. In all but two cases, these inconsistencies follow a pattern: experts tended to be more conservative when providing percentile cost estimates, while they associated slightly higher probabilities when facing the probability question. Differences are small, in the order of 5 to 10 percentile points. Experts almost unanimously conformed to the more conservative figures when revising their numbers during the follow-ups.

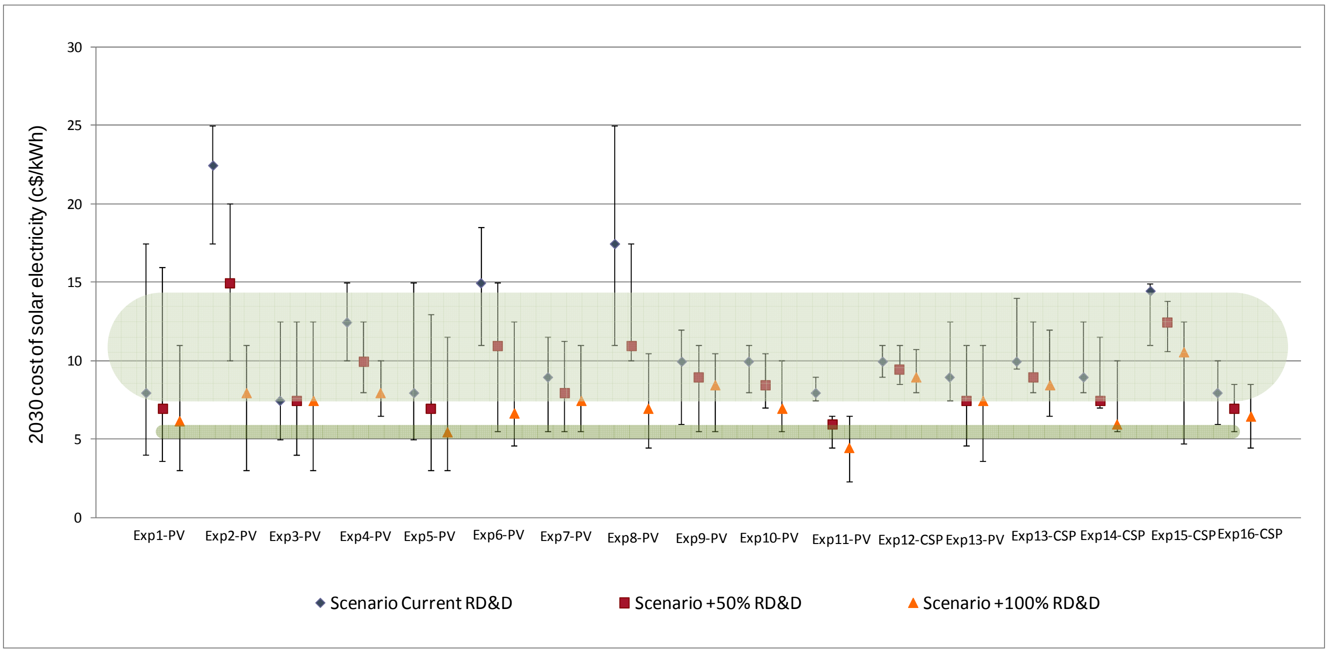

Figure 6. Estimates of 2030 solar electricity costs (50th, 90th and 10th percentiles) under different EU RD&D funding scenarios. Experts 13-16 provided cost estimates for CSP technologies, while the others considered PV technologies. The light green area defines the 2020 range of expected cost of electricity produced from PV: from 7.3 cUSD/kWh (Breyer et al. 2009) to 14.5 cUSD/kWh (IEA, 2010b). The green area represents the 2020 US Department of Energy goals for CSP (Arvizu et al., 2011): from 5 to 6 cUSD/kWh. The 2030 CSP cost projections from IEA are somewhat higher, ranging from 10.7 to 15.6 cUSD/kWh by 2030 (IEA, 2010a).

Let us first concentrate on expected costs under current RD&D scenario (blue markers in Figure 6). Experts 12, 14 and 15 provided 2030 cost estimates for CSP technologies, while all other experts provided 2030 cost estimates for the best performing PV technology, in most cases without specifying which technology they were referring to. The only exception is expert 2, who specifically considered concentrating PV technologies. Most experts' best guesses lay within the 7.5 - 14.5 cUSD/kWh range. This is in line with estimates reported in the IPCC Report (Arvizu et al., 2011). The average expected cost[12] resulting from the experts' estimates is 11.7 cUSD/kWh, while it falls to 10.8 cUSD/kWh when Expert 2 is excluded. The average expected cost for only CSP technologies is 10.1 cUSD/kWh. This value is well above the 2020 US Department of Energy goals for CSP as reported in Arvizu et al. (2011) and more in line with the 2030 cost projections from IEA, which range from 10.7 to 15.6 cUSD/kWh (IEA, 2010a).

Under the "+50% RD&D" scenario (red markers in Figure 6), the estimated costs are on average 20% lower: the majority of estimates ranges from 7 to 11 cUSD/kWh and the average expected cost is 9.3 cUSD/kWh,[13] while for CSP the average expected cost is 8.9 cUSD/kWh.

The average expected cost conditional under the "+100% RD&D" (yellow markers in Figure 6) is 7.7 cUSD/kWh, with most estimates ranging from 6 to 9 cUSD/kWh, while the average expected costs for CSP technologies is 8.1 cUSD/kWh.

[12] Expected costs are computed by using all six point of their probability distribution provided by each experts.
[13] Leaving out expert 2 does not significantly change the average expected cost figure: under the +50% RD&D scenario divergence across experts is reduced.

All experts agree on the link between RD&D investments and expected costs: higher RD&D expenditures are associated with lower average expected costs. However, their opinions vary widely with respect to the effect of RD&D on uncertainty, which is represented by the support of the distribution , namely the length of the bar in Figure 2. . According to six out of sixteen experts, the "+50% RD&D" scenario reduces the uncertainty surrounding costs. However, increasing public funding further (+100% scenario) results in higher uncertainty. Twelve experts provided wider cost ranges for at least one of the two "higher-than-current RD&D" scenarios. This indicates a higher degree of uncertainty in evaluating departures from the *status quo*. This, as explained by some of the experts, depends on budget allocation: 100% growth in the solar RD&D funds would probably result in higher investments in less mature technologies, whose success has a greater degree of uncertainty respect to more mature technologies.[14].

It is hard to compare the estimates presented in this study with those of similar previous contributions (i.e. Curtright et al., 2008 and Baker et al., 2009a) due to the differences in assumptions and focus. However, it is apparent that the estimates we report are generally more optimistic and less dispersed than those Curtright et al. (2008) where all interviewed experts reported a probability greater than 70% that expected cost in 2030 would be below 24 cUSD/kWh, for at least one of the PV technologies analyzed. [15] Baker et al. (2009a), conversely, focused specifically on second generation PV technologies. By assessing the evolution of specific technical endpoints[16] they collected greatly dispersed probabilities (the values ranged between 0 and 40%) associated to the 2050 costs of electricity being below 5 cUSD/kWh.

Using the experts' estimates under the three different RD&D scenarios we estimate a learning rate by fitting a learning-by-researching model (see Kouvaritakis, et al, 2000, among others). In this model, the cost of the technology in 2030, C_{2030}, is a function of the stock of knowledge in 2030 (RD_{2030}), the stock of knowledge at current time, RD_{2010} and the cost at current time, C_{2010}:

$$\frac{C_{2030}}{C_{2010}} = \left(\frac{RD_{2030}}{RD_{2010}}\right)^{\beta} \quad (1)$$

Where β is the learning coefficient and the implied learning-by-researching rate is equal to $1-2^{\beta}$. We used the experts estimates of the cost in 2030 as a proxy for C2030, and calculated the cumulated investments in R&D based on the assumptions we provided and using the perpetual inventory method (see Peri 2005 and Verdolini and Galeotti, 2011 among others) with discount rates ranging from 5% to 25%. Equation (1) was estimated in log-linear form by 17 pooling all experts' estimates. The resulting estimates for coefficient ß range from -0.13 to -0.9 and are significant at the 1% level independently of

[14] For more information see Bosetti et al., 2011

[15] Curtright et al. (2008) make specific assumptions on technical factors such as lifetime, capacity factor, balance of system costs, etc. Specifically, they assume future capital prices of 1.20USD$, a module lifetime of 25 years and no decrease in power output over that period, a capacity factor of 15%, a 12% capital charge rate, annual maintenance of 0.5% of the capital cost, and balance of system costs equal to the cost of the modules.

[16] The technical endpoints considered in Baker et al. (2009a) were efficiency, lifetime and cost of manufacturing over the next 40 years. Specifically, a cost of electricity of 5 cUSD/kWh corresponds to 15% efficiency, 30 year lifetime and 50 USD/m^2 of manufacturing costs, while a cost of electricity of 3 cUSD/kWh corresponds to 31% efficiency, 15 year lifetime, 50 USD/m^2 of manufacturing costs.

[17] Sensitivity analysis of these results were carried out by varying the discount rate from 5% to 25%. Results are qualitatively similar and are available from the authors upon request.

the discount rate and of the inclusion or exclusion of fixed effects controlling for each expert's identity. The implied learning rate thus ranges between 7% and 9%. Such an estimate is in the lower range of learning rates reported previously in the literature as for example in (Kobos, et al. 2006).

4. Non-technical barriers and diffusion of solar technologies

The potential for success of solar technologies cannot be assessed simply considering technical barriers, future development and the cost-reducing potential of RD&D programs. Although cost competiveness is a key driver for solar technologies deployment, non-technical issue and barriers could still play a big role in slowing down worldwide diffusion. The final section of the survey addressed precisely this point.

We first asked experts which geographical area of the world has the highest probability of being the first to reach commercial success in solar technologies. 35% of the experts indicated that the breakthrough will first take place in the EU, while 29% indicated China. Only 23% and 13% of the experts believe that success will be achieved in the United States and Japan, respectively. Keeping in mind that the pool of experts we selected was European, these responses could be partly biased by the geographical origin of the experts.

However, the strong policies implemented at the EU level both with respect to demand and supply determinants of technological development have fostered the European leadership in solar technologies and are indicative of a high chance that cost-competitiveness could occur in the EU first. As already mentioned, public investment in solar technologies is higher in the EU than in the USA. Moreover, the EU is characterized by the presence of clear political support and specific policies for renewable energy penetration. These are key factors to ensure that currently available technologies exit the so-called "valley of death" of Demonstration and Deployment. This testifies the great collective effort of Member States with respect to cost-competitive solar technologies. In this sense, the bias in experts' estimates is likely to be low.

Figure 7 summarizes the main non-technical barriers to the widespread diffusion of solar technologies. First, past capital investments in fossil power plants make it hard to switch to a new technology before the end of the plants' commercial life. This is known as the "lock-in" effect due to sunk costs and long-lived capital. Unless direct policy intervention accelerates capital turnover, it is unlikely that solar technologies and other alternative electricity sources will diffuse rapidly. Second, renewable energy sources feeding into an electric power grid do not receive full credit for the value of their power unless specific supporting policies are in place. Such unfavourable power pricing rules need to be overcome by policy intervention. Third, intermittency in the supply of solar power should be overcome with adequate storage systems and better grid integration. Other non-technical barriers are the availability of rare metals for some specific PV and CSP infrastructures, as well as land availability and other geographical constraints (e.g. sun irradiation). The relative importance of these last barriers is low compared to the other three previously mentioned. Some concern was mentioned about land use and soil occupation, with a call for a careful definition of the site and the design of the facility.

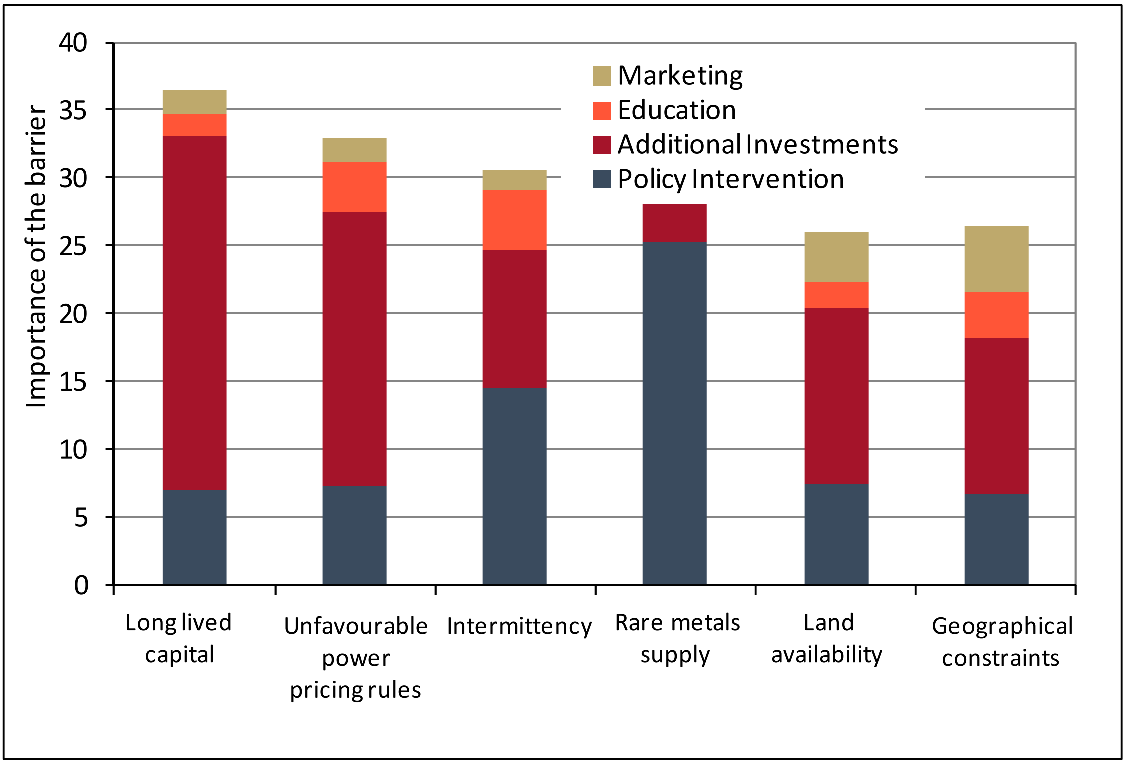

Figure 7. Non-technical barriers to the diffusion of solar technologies and potential solutions to overcome the barriers. Each expert scored barriers on a scale from 0 to 3, with 3 indicating high importance. Bars indicate the sum of score across all experts.

With respect to the use of toxic components (i.e. CdTe toxicity), most experts reported that industries in the PV sector are advanced in the management and recycling of toxic substances and therefore did not share concerns on this particular issue.[18]

Experts were also asked to reflect on how non-technical barriers to market diffusion would influence the penetration of solar technologies in different geographical areas. Under the assumption that in 2030 solar technologies would be cost-competitive with conventional fossil fuels, experts provided their estimates with respect to alternative penetrations scenarios (low, medium or high penetration rates) in three different regions, namely OECD, developing countries and fast-growing countries. The scenarios assumed that solar power could represent (1) between 0 and 5%, (2) between 6 and 20% and (3) between 21 and 30% of the electricity generation mix in 2050. Results of their estimates are shown in Figure 8.

[18] 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 instead would raise issues related to their visual impact and local environmental effects. Again, siting would be a critical factor with the potential emergence of NIMBY (Not-In-My-Back-Yard) effects. Moreover, water requirements for cooling purposes represent a clear limit for the large scale deployment of solar technologies in hot and dry places. A possible solution in this respect would be the development of dry cooling.

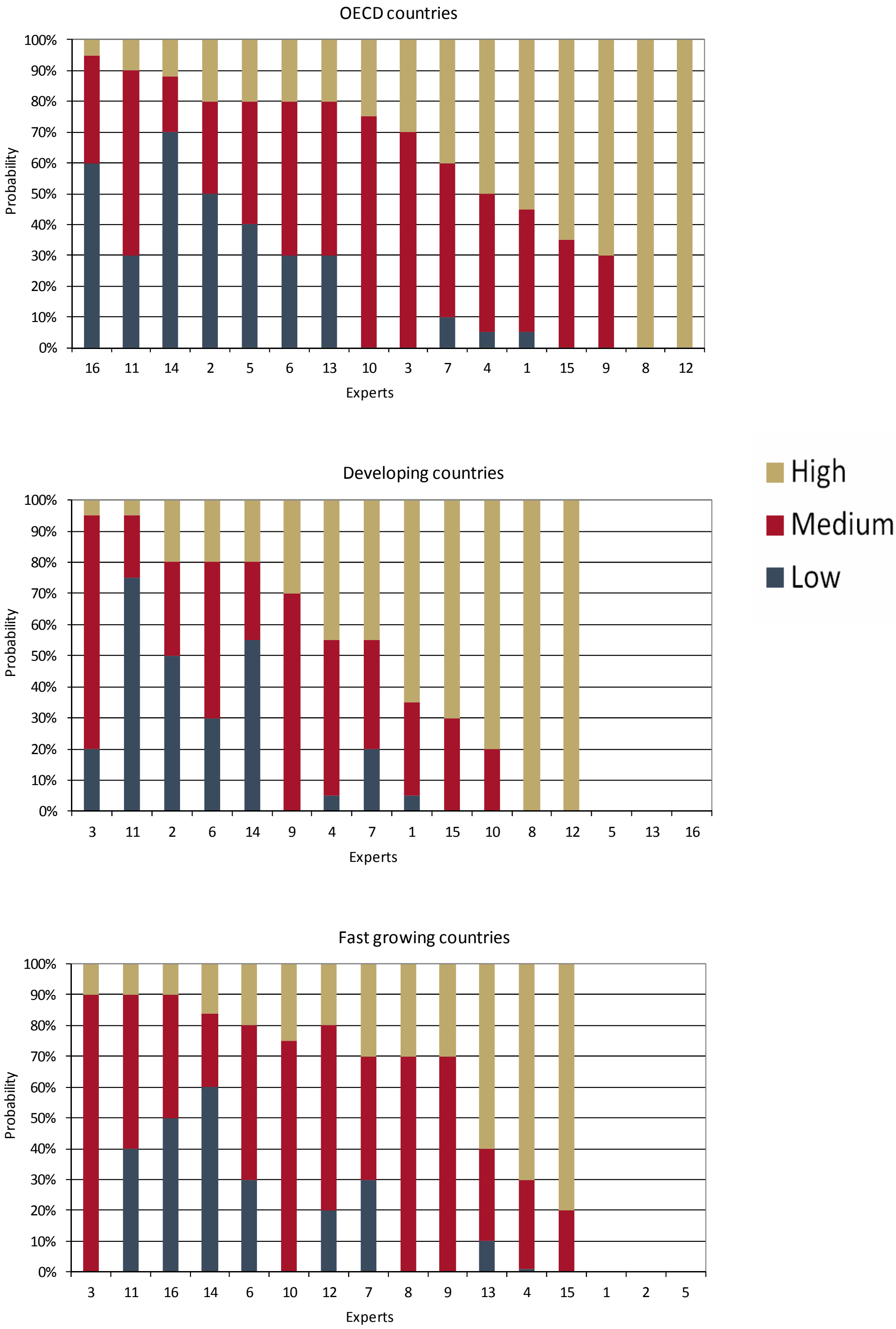

Figure 8. Percentage of solar technologies in power generation mix in 2030. Figure indicates the likelihood that each expert associates with the three penetration scenarios of solar power in total power generation mix (low=between 0% and 5%, medium= between 6% and 20% and high=between 21% and 30%).

On this issue, experts show very little consensus. Almost 40% of the experts assign more than 50% probability that OECD countries will experience a high penetration scenario by 2050. Conversely, half of the experts believe that the high penetration scenario is the most likely in developing countries. The argument supporting higher penetration rates in developing countries than in fast-growing countries is that solar technologies would not have to overcome problems of substituting existing power infrastructures. Finally, the majority of experts agree that the middle scenario is the more likely in fast-growing countries.

A final question asked the experts what would be the maximum share of global electricity that could be produced by solar technologies after 2050. Ten experts specified a ceiling slightly higher than 30% of total power generation, while only three specified a ceiling higher than 50%. All experts recognize that shares of solar electricity higher than 30% would require significant investments to further improve electricity storage, the management of variable power and the compensation of intermittency, as well as resources and land availability.

Generally, the conclusions reached by the experts on technology diffusion are in line with the projections shown in the IPCC Special Report on Renewable Energy Sources (Arvizu et al, 2011). These are based on a set of scenarios reviewed under the IPCC Fourth Assessment Report and describe a very wide range of possible trends in terms of potential contribution of solar energy in the global electricity supply.

5. Conclusions and policy recommendations

This analysis was motivated by the need to evaluate the impact of RD&D investment on the future cost of solar technologies in the context of their fast recent evolution. Assessing the RD&D effort necessary to promote cost-competitiveness and to overcome non-technical diffusion barriers is a key step to support policy makers in drafting appropriate efficient energy policies. The evidence we provided in this paper summarizes the estimates of 16 leading European experts which were derived from a robust elicitation protocol. They indicate that a stable RD&D funding to solar technologies is crucial given the strong link between RD&D investments and (lower) solar electricity cost. The primary condition for substantial technical improvements is the long term commitment to a constant RD&D effort in the range of the pre-economic crisis levels.

If constant public support for solar technologies is secured, at least one of the solar technological options analyzed in this study has a high potential to overcome technical bottlenecks in the next 20 years and to become cost-competitive with fossil fuel electricity production. Our analysis suggests that the best chances for success are linked with the development of a diversified portfolio of public RD&D funding in solar technologies. Funds should be allocated both to PV and CSP technologies, and support should be secured for more mature technologies (such as Crystalline-silicon and Thin-film PV) and more innovative ones (such as Organic PV and Third Generation PV). All experts indicate that more mature technologies should receive most of the funds, while minor amounts should be allocated to less mature ones. Some funding for less mature technologies should be provided nonetheless, in an effort to clearly assess their potential. Policy makers should avoid “picking the winner” and should let technological options compete to a certain extent, while ensuring that all of them are explored thoroughly.

One key insight of this study is on the importance of appropriately supporting the full RD&D process. In contrast with the historical institutional choice of the EU and its Member States, the experts indicate that demonstration activities should be a core element in the innovation strategy for solar technologies. This will ensure that the more mature technologies exit the “valley of death” and become commercially viable.

Experts' subjective estimates of solar electricity costs are different under the three funding scenarios we propose in our elicitation. In a "current RD&D" scenario, most experts' estimates lay within the 7.5-14.5 cUSD/kWh range. The average expected cost for PV (CSP) technologies is 10.8 (10.1) cUSD/kWh. In this scenario, the average expected costs would be below the symbolic threshold of 11 cUSD/kWh, namely the price of coal electricity with a carbon price of 30 USD per ton of CO2.

Increasing RD&D funding by 50% ("+50% RD&D" scenario) lowers expected costs by roughly 20%, bringing the average cost to 9.3 (8.9) cUSD/kWh for PV (CSP) and with less variance in experts' estimate. In this scenario, the probability that costs will be below the 11 cUSD/kWh threshold by 2030 is higher, reaching 78% (from 66%). Under the "+100% RD&D" scenario basically all experts agree that the cost of solar electricity would be lower than 11 cUSD/kWh, with a probability of breakthrough higher than 90%.

Our analysis shows that, unless public RD&D investment increases, the probability that solar electricity will cost 5.55 cUSD/kWh or less is smaller than 10%. Specific climate policy need to be put in place, solar technologies are unlikely to become cost-competitive with fossil fuel technologies. The picture does not change substantially under the increased RD&D investment scenarios. The average probability of reaching 5.55 cUSD/kWh rises to 12% and 21% in a "+50% RD&D scenario" and a "+100% RD&D scenario", respectively.

The majority of the experts are pessimistic with respect to the possibility of reaching lower ideal cost thresholds. Solar technologies, while being viable options for the future, are and will most likely remain intrinsically more expensive than fossil fuels unless the environmental externalities associated with the use of hydrocarbons are internalized through a carbon tax or other policy mechanisms. This vision is partly mitigated by the belief that dispersed power production through solar panels might be the most viable option to grant access to electricity in rural areas of developing countries.

What emerges from the interviews is the evident effort undertaken in Europe with respect to solar technology development and the high probability that the EU will first achieve a breakthrough in production costs. However, experts recognize that other countries too (both developed, such as the USA, and developing, such as China) have a high probability of producing cost-competitive solar technologies. This clearly points to the importance of implementing a well-designed RD&D strategy that capitalizes on the comparative advantage of EU countries and gives them a cutting edge in this important field.

The experts acknowledged that non-technical issues and obstacles could slow down the worldwide diffusion of solar technologies. The major barriers are the inertia of existing power plants and unfavorable power pricing rules, which need to be addressed through ad hoc policy interventions, such as feed-in tariffs. When assessing the likelihood that solar power will represent 5%, 20% and 30% of electricity production in OECD countries, experts show little consensus. Almost 40% indicate penetration in the OECD countries will be high (around 30%). Fast-developing countries will instead experience an average diffusion scenario, while developing countries are assigned a high probability of experiencing high penetration rate since lock-in effects will be milder.

We believe the results presented so far and the policy implications resulting from this elicitation exercise are of great relevance for the current debate on renewable energy technologies in Europe and worldwide. Our data can also be used as input to integrated assessment and energy models. These models, used to design and assess the effect of both energy and climate policy, are usually poor in their description of innovation and technological change, while assumptions about technologies, their availability and costs crucially affect their projections (Grubb et al. 2006). Probabilistic information on future cost and penetration potentials of technological option as relevant as solar can be used to improve this class of models, hence augmenting the reliability on the derived projections and assessments. This is where our future research effort will focus.

References

Arvizu, D., Balaya, P., Cabeza, L., Hollands, T., Jäger-Waldau, A., Kondo, M., Konseibo, C., Meleshko, V., Stein, W., Tamaura, Y., Xu, H., Zilles, R., 2011. Direct Solar Energy, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., v. Stechow, C. (Eds.), IPCC Special Report on renewable energy sources and climate change mitigation. Cambridge University Press, Cambridge and New York.

Baker, E., Chon, H., Keisler, J., 2009a. Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy. Energy Economics 31, S37-S49.

Baker, E., Chon, H., Keisler, J., 2009b. Carbon capture and storage: combining economic analysis with expert elicitations to inform climate policy. Climatic Change 96, 379-408.

Baker, E., Keisler, J.M., 2011. Cellulosic biofuels: Expert views on prospects for advancement. Energy 36, 595-605.

Bloomberg, 2009. New Energy Finance, http://bnef.com/.

Bosetti, V., C. Carraro, E. Massetti, A. Sgobbi and M.Tavoni, 2009. Optimal Energy Investment and R&D Strategies to Stabilise Greenhouse Gas Atmospheric Concentrations, Resource Energy Economics, Volume 31, Issue 2, May 2009, Pages 123-137 doi:10.1016/j.reseneeco.2009.01.001

Bosetti, V., Catenacci, M., Fiorese, G., Verdolini, E., 2011. Solar PV and CSP technologies. Policy recommendations from the ICARUS survey on current state and future developments. ICARUS Report 1, Milan.

Breyer, C., Gerlach, A., Mueller, J., Beacker, H., Milner, A., 2009. Grid-parity analysis for EU and US regions and market segments - Dynamics of grid-parity and dependence on solar irradiance, local electricity prices and PV progress ratio. 24th European Photovoltaic Solar Energy Conference, Hamburg, Germany, 21-25 September 2009.

Chan, G., Anadon, L.D., Chan, M., Lee, A., 2011. Expert elicitation of cost, performance, and RD&D budgets for coal power with CCS. Energy Procedia 4, 2685-2692.

Clemen, R.T., Reilly, T., 2001. Making hard decisions with decision tools. Duxbury/Thomson Learning, Belmont CA.

Cooke, R. M., (1991) Experts in Uncertainty, Oxford University press.

Cooke, R.M., Goossens, L.J.H., (1999), Procedures guide for structured expert judgements, Project Report to the European Commission, EUR 18820.

Curtright, A.E., Morgan, M.G., Keith, D.W., 2008. Expert assessments of future photovoltaic technologies. Environmental Science & Technology 42, 9031-9038.

Denholm, P., Drury, E., Margolis, R., Mehos, M., 2010. Solar energy: The largest energy resource, in: Sioshansi, F. (Ed.), Generating Electricity in a carbon-constrained world. Academic Press, Boston.

EC – European Commission, 2009. R&D Investment in the Priority Technologies of the European Strategic Energy Technology Plan. Commission Staff Working Document SEC(2009) 1296.

Ginley, D., Green, M.A., Collins, R., 2008. Solar energy conversion toward 1 terawatt. Mrs Bulletin 33, 355-364.

Grubb, M., Carraro, C. & Schellnhuber, J., 2006. Technological change for atmospheric stabilization: introductory overview to the innovation modeling comparison project. Energy Journal, 27, pagg.1–16.

Hogarth, R. (1987) Judgement and Choice Wiley, New York.

HSBC, 2009. The green rebound. Clean Energy to become an important component of global recovery plans. 19 January 2009

IEA – International Energy Agency, 2010a. Technology Roadmap, Concentrating Solar Power. OECD/IEA, Paris.

IEA – International Energy Agency, 2010b. Technology Roadmap, Solar Photovoltaic Energy. OECD/IEA, Paris.

IEA – International Energy Agency, 2011. RDD Budgets Database, Paris. Accessed April 2011.

Jäger-Waldau, A., Szabó, M., Monforti-Ferrario, F., Bloem, H., Huld, T., Lacal Arantegui, R., 2011. Renewable Energy Snapshots 2011, JRC Report Available at http://re.jrc.ec.europa.eu/refsys/pdf/RE_Snapshots_2011.pdf

Keeney, R.L., von Winterfeldt, D., 1991. Eliciting probabilities from experts in complex technical problems. IEEE Transactions on Engineering Management 38, 191-201.

Kobos, P.H., Erickson, J.D. & Drennen, T.E., 2006. Technological learning and renewable energy costs: implications for US renewable energy policy. Energy policy, 34(13), pagg.1645–1658.

Kouvaritakis, N., Soria, A. & Isoard, S., 2000. Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. International Journal of Global Energy Issues, 14(1), pagg.104–115.

Meyer, M.A., Booker, J.M., 1991. Eliciting and analyzing expert judgment: A practical guide. Academic Press Ldt, London.

Morgan, G., Henrion, M., 1990. Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press, New York.

Nemet, G.F., 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy, 34(17), 3218–3232.

O'Hagan, A., Buck, C.E., Daneshkhan, A., Eiser, J.R., Garthwaite, P.H., Jenkinson, D.J., Oakey, J.E., Rakow, T., 2006. Uncertain judgments: Eliciting experts' probabilities. John Wiley & Sons, Ltd., Chichester.

Peri, G., 2005. Determinants of knowledge flows and their effects on innovation, The Review of Economics and Statistics 87 (2), 308–322.

Phillips, L.D., 1999. Group elicitation of probability distributions: Are many heads better than one?, in: Shanteau, J., Mellers, B., Schum, D.A. (Eds.), Decision science and technology: Reactions on the contributions of Ward Edwards. Kluwer Academic Publishers, Norwell.

Price, H., Lupfert, E., Kearney, D., Zarza, E., Cohen, G., Gee, R., Mahoney, R., 2002. Advances in parabolic trough solar power technology. Journal of Solar Energy Engineering-Transactions of the Asme 124, 109-125.

Robins, N., Clover, R., Singh, C., 2009. A Climate for Recovery, The colour of stimulus goes green, HSBC report.

Tversky, A. & Kahneman, D., 1974. Judgment under uncertainty: Heuristics and biases. science, 185(4157), 1124.

Verdolini, E., Galeotti, M., 2011. At home and abroad: An empirical analysis of innovation and diffusion in energy technologies, Journal of Environmental Economics and Management 61, 119–134

Walls, L., Quigley, J., 2001. Building prior distributions to support Bayesian reliability growth modelling using expert judgement. Reliability Engineering & System Safety 74, 117-128.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2012

CCSD	1.2012	Valentina Bosetti, Michela Catenacci, Giulia Fiorese and Elena Verdolini: The Future Prospect of PV and CSP Solar Technologies: An Expert Elicitation Survey