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Innovation for Climate chAnge mitigation:
a study of energy R&d, its Uncertain
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Icarus expert elicitation reports

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Policy recommendations from the ICARUS survey on current state and future developments

by Valentina Bosetti, Michela Catenacci, Giulia Fiorese, Elena Verdolini

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Content

List of experts

This report was possible thanks to the proactive participation of the following experts:

Table 1: List of experts participating in the survey

Name and Surname	Affiliation	Country
Aldo Di Carlo	UniRoma2, Opto&Nanoelectronics Group	Italy
Antonio Luque	Instituto de Energía Solar, Universidad Politecnica de Madrid (IES)	Spain
Arnulf Jäger-Waldau	European Commission, DG JRC	Germany
Carlos del Canizo Nadal	Universidad Politecnica de Madrid (IES)	Spain
Christoph Richter	German Aerospace Center, Institute of Technical Thermodynamics	Germany
Ferrazza Francesca	Ente Nazionale Idrocarburi (ENI)	Italy
Luisa F. Cabeza	University of Lleida	Spain
Ole Langniss	Fichtner - Engineering and Consulting Services	Germany
Paolo Frankl	International Energy Agency (IEA)	UK
Paolo Martini	Archimede Solar Energy (Angelantoni Group)	Italy
Paul Wyers	Energy Research Centre (ECN)	The Netherlands
Rob Bland	McKinsey (Silicon Valley)	US
Roberta Campesato	Centro Elettrotecnico Sperimentale Italiano (CESI)	Italy
Roland Langfeld	Schott AG. Research and Technology Development	Germany
Rolf Wüstenhagen	Institute for Economy and the Environment, University of St. Gallen	Switzerland
Wim Sinke	Energy Research Centre (ECN)	The Netherlands

Please note that the numbers associated to the experts in the paper are randomly assigned

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Executive summary

The present report puts forward a set of policy recommendations derived from the expert elicitation survey on solar technologies carried out within ICARUS, a 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).

Sixteen leading European experts from the academic world, the private sector, and international institutions took part in the ICARUS expert elicitation survey on Photovoltaic (PV) and Concentrated Solar Power (CSP) technologies. The survey collected probabilistic information on (1) the role of RD&D investments with respect to lowering future costs of these technologies and (2) the potential for their deployment (both in OECD and non-OECD countries). The information gathered from the experts sheds light on the evolution of the future costs of solar technologies and results in a number of important policy recommendations with respect to solar RD&D investment. Results can be summarized as follows:

RD&D efforts

- The primary condition for substantial improvements in the cost competitiveness of the next generation of solar technologies is the long-term commitment to a constant RD&D effort in the range of the pre-economic crisis levels. Given this evidence, the EU and its Member States should plan a long-term commitment to secure stable RD&D funding to solar technologies.
- Most experts suggest diversified RD&D portfolios so that a variety of technological alternatives can be kept open. To this end, RD&D funding for relatively more mature technologies (such as Silicon-based PV and CSP) as well as for frontier technologies (such as Organic and Third Generation PV) should be secured. This implies that rather than "picking a winner" policy-makers should let technological options compete, although ensuring they all keep on existing.
- Demonstration should become a key area of funding. To this end, the EU and its Member States should support the demonstration phase alongside private sector investors.

Evolution of solar technology costs

- Expected costs of solar power in 2030 range between 8 cUSD/kWh and 22 cUSD/kWh, under the assumption that current RD&D funding remains stable for the next twenty years. Both the upper and lower bounds of this range are defined by PV technologies, while the cost range for CSP technologies is smaller (8.2-13.7 cUSD/kWh).
- Assuming a mild carbon policy (corresponding to 11.5 USD per ton of CO_2 in 2030) solar power would very likely become cost competitive with coal fuelled power according to almost all the experts.
- If no carbon policy is in place almost all experts agree that no increase in RD&D funding would be sufficient to make solar power cost competitive with coal-generated power by 2030.
- Increasing the current levels of RD&D effort by 50% reduces the high ends of the expected cost range of most pessimistic experts. As the consensus surrounding future expected costs of solar power is small, higher

RD&D expenditures represent a lever to reduce the uncertainty over future returns of innovation.

- Increasing RD&D from current levels would also accelerate breakthroughs in less mature technological options, thus increasing the (small) likelihood of very large returns.

Solar diffusion

- Experts recognize the efforts undertaken in Europe in terms of RD&D spending, innovation and public policies by attaching to a European country the highest likelihood of being the first country to reach a breakthrough in production costs. However, experts recognize that also other countries (both developed, such as the USA, and developing, such as China) have a high probability of producing cost-competitive solar technologies.
- All experts emphasize the crucial role of non-technical barriers to the diffusion of solar technologies (such as long-lived capital stock of current fossil fuel power plants and unfavourable pricing rules). This calls for policy intervention, in the form of a price on carbon, feed-in tariffs or standards, to secure penetration.
- The share of total electricity produced using solar technologies by 2050, even according to the most optimistic experts, will not be greater than 30%. When assessing the likelihood that solar power will represent 5%, 20% and 30% of electricity production in OECD countries, experts show very little consensus. Conversely, with respect to fast-developing countries the majority of experts associates the highest likelihood to the 20% scenario. When considering developing countries, half of the experts assign the highest probability to the 30% penetration scenario. The rationale behind this view is that in developing countries lock-in effects will be less a barrier to development than in fast growing countries.
- Advancements in energy storage technologies will be critical in order to reach a share of electricity production from solar higher than 30%. Although this is a longer term issue, RD&D should be devoted to envision solutions.

1. Introduction

The present report illustrates the outputs of the expert elicitation survey on Photovoltaic (PV) and Concentrated Solar Power (CSP) technologies carried out within the “Innovation for Climate chAnge mitigation: a study of energy R&D, its Uncertain effectiveness and Spillovers” (ICARUS) project, a 3-year ERC-funded project on innovation in carbon-free technologies (www.icarus-project.org).

ICARUS focuses on three interconnected streams of research relating to energy-efficient and environmentally-friendly frontier (or breakthrough) technologies, namely:

1. Understanding the dynamics and drivers of innovation and knowledge flows using different data inputs (such as patents or Research, Development and Demonstration (RD&D) expenditures);
2. Eliciting European experts’ opinion on the likelihood of reaching commercial success (breakthrough) and widespread diffusion;
3. Assessing optimal energy RD&D portfolios under different climate targets in face of both innovation and policy uncertainty. To this end, the results of the first two research streams are projected into the future by means of an Integrated Assessment model.[1]

The survey on PV and CSP technologies directly relates to the second stream of research and focuses on eliciting probabilistic information on the future costs of solar technologies and on the potential role of RD&D in reducing these costs. To this end, we collected information from sixteen experts (listed in Table 1) coming from different EU Member States and belonging to the academia, the private sector and to international institutions. This provides novel evidence on the likely evolution of solar costs in the next decades and on the range of the uncertainty surrounding them, thus complementing the insights obtained from climate economy models. The analysis of the experts’ data results in a number of important policy recommendations to guide the RD&D choice and commitment of the EU and its Member States in future years.

PV and CSP technologies represent an important option for electricity production and could significantly contribute to lowering CO_2 emissions from fossil fuel use. Solar technologies can play a role as an off-grid solution to alleviate energy poverty. This is particularly important for developing countries, where electrification rates are lower and solar technologies may grant access to electricity for lighting, communication and entertainment purposes (Abdullah and Markandya, 2009; Wamukonya, 2007; Jacobson, 2007). Solar technologies represent a particularly palatable option for both developed and developing countries as, together with other renewable sources, they could significantly improve energy security while abating local pollution.

The contribution of solar to renewable energy supply is still marginal. In 2007, solar PV accounted for 0.6% and 0.1% of renewable energy

[1] WITCH is an Integrated Assessment model developed by the Climate Change Research Group at FEEM (see www.witchmodel.org for further details, a list of applications and selected research papers).

generation in OECD EU countries and the USA, respectively. PV in the last ten years grew at a 40% rate per year (IEA, 2010b).

Germany leads the OECD's solar PV installation with a 5.3 GW capacity. Other leaders are Spain (3.4 GW), Japan (2.1 GW) and the United States (1.2 GW). These four countries combined represent 85.8% of the OECD's solar PV energy supply (IEA, 2010c). Despite the recent economic crisis, the PV market is gaining momentum. A number of countries, including Australia, China, France, Greece, India, Italy, Korea and Portugal, provided much support to PV in recent years. As a result, economic support schemes more than doubled between 2009 and 2010. Conversely, CSP systems are currently mainly concentrated in the United States and Spain, with few installations under construction in Northern Africa (NREL, 2010).

The EU and its Member States have included PV and CSP technologies among the technology options which need to be promoted to move towards sustainable energy use (see the EU requirements for 2020 in Directive 2009/28/EC). For these technologies, the barriers, the scale of the investment and risk involved can be better tackled collectively.

The main challenge hindering the widespread deployment of PV and CSP technologies is their costs, which is currently not competitive with fossil fuel technologies (either with or without the help of a price on carbon). Solar power production 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). Understanding the relative role of each of the barriers hindering diffusion is a crucial exercise that would result in more targeted and effective policy interventions. The survey focuses on both cost-competitiveness and non-technical barriers for deployment.

Through an elicitation protocol we surveyed experts to collect probabilistic information on the future cost of solar technologies, how this will be affected by EU public RD&D programs, and what non-technical barriers to diffusion should be carefully considered when planning renewable energy policies. The questionnaire was divided in five sections, each one gathering expert opinions and reactions on a specific issue (the full version of the questionnaire is provided in Annex I):

1. Reference data on solar technologies, current cost estimates and current RD&D investments for PV and CSP technology options, as detailed in Figure 1.
2. Identification of existing technical barriers preventing the success of solar technologies and 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 these might be affected by different RD&D programs.
5. Potential for solar technology diffusion, the role of technology transfer dynamics and non-technical barriers.

The elicitation protocol that we developed builds upon a vast literature (Morgan and Henrion, 1990; O'Hagan et al., 2006; Meyer and Booker, 1991; Clemen and Reilly, 2001; Keeney and von Winterfeldt, 1991; Phillips, 1999;

Walls and Quigley, 2001) but contains a number of important innovative elements:

- *European perspective:* We provide the first elicitation of European experts. Expert elicitation has been widely used in the USA to gather probabilistic information on the future potential of energy technologies and to inform policy makers (e.g., Baker et al., 2009a, 2009b; Baker and Keisler, 2011; Curtright et al., 2008; Chan et al., 2010), but so far it has not been carried out in Europe.
- *Global focus*: We broaden the research horizons by focusing on the potential 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 important markets for the deployment of these technologies. While we ask the experts to assess the potential for cost reductions conditional on RD&D investments in European countries, we ask them to also consider the potential for technology deployment and diffusion worldwide. In particular, looking into knowledge spillovers and technology transfer dynamics, experts indicate where commercial breakthrough is expected to occur, and how solar technologies would spread across different countries and regions of the world.
- *Broad set of technologies*: Unlike previous studies, we assess the evolution of both PV and CSP technologies. The potential of PV technologies as a low-cost no-carbon option has been addressed in few previous studies (Baker et al., 2009a; Curtright et al., 2008) which analysed either one or several PV technology options. Conversely, there is no previous expert elicitation on CSP technologies. Conditional on technological improvements, CSP has great potential as a large scale technology option with competitive electricity prices. The IEA estimates that CSP could provide more than 50% of solar power by 2050 (IEA, 2010b). Understanding how investments in RD&D contribute to making this option cost-competitive and commercially viable is therefore of great relevance for policy makers. Assessing jointly the potential of PV and CSP technologies also allows a comparison between these two technology options.
- *Diffusion*: Rather than concentrating solely on cost reductions conditional on RD&D investment levels, we also investigate the non-technical conditions that could set back the technology's diffusion into the market. Such barriers could prevent technology diffusion even if solar technology became cost-competitive with traditional fossil fuels. Barriers include difficulties with the turnover of existing power plants, unfavourable power pricing rules and geographical constraints. Some of the potential solutions to overcome such challenges are policy measures, financial incentives, education programs or marketing interventions.

The next section of the report briefly reviews the current status of solar PV and CSP technologies. Section 3 illustrates the characteristics of the expert elicitation process and provides information on the origin and level of expertise of the experts. Section 4 describes the technical potential of the different PV and CSP technologies and illustrates the necessity to efficiently allocate the RD&D budget to overcome the technical barriers and consequently lead solar technologies to commercial success. Section 5 presents the experts' assessment of the role of RD&D investments in reducing the cost of electricity produced with solar technologies. Section 6 analyses technology transfer dynamics and various scenarios of market diffusion. Section 7 summarizes the main findings of this study.

2. Solar technologies today

The expert elicitation survey carried out within the ICARUS project focuses on 6 families of technologies for solar electricity production, namely Crystalline-silicon Photovoltaic (PV), Thin-film PV, Concentrating PV, Organic PV, Third Generation PV and Concentrated Solar Power (CSP) (Figure 1). We focus on a wide range of technologies (more and less innovative) because even for the most mature ones (such as Crystalline-silicon PV) there still is a strong need for research and technical improvements (Ginley et al., 2008).

PV technologies represent an extremely interesting option for distributed electricity generation. The technology is relatively simple, modules are flexible and do not require expensive maintenance. Moreover, innovative technologies, like organic PV, will allow for the integration of modules in buildings and in new commercial products, providing infinite new possibilities for the exploitation of solar energy.

CSP technologies, on the other hand, are promising because of their large scale potential. These systems use concentrating collectors for the solar radiation and heat a working fluid to high temperature, thus producing the steam necessary to spin a turbine and generate electricity. The plant is usually equipped with thermal storage allowing to partly address the issue of power generation intermittency.

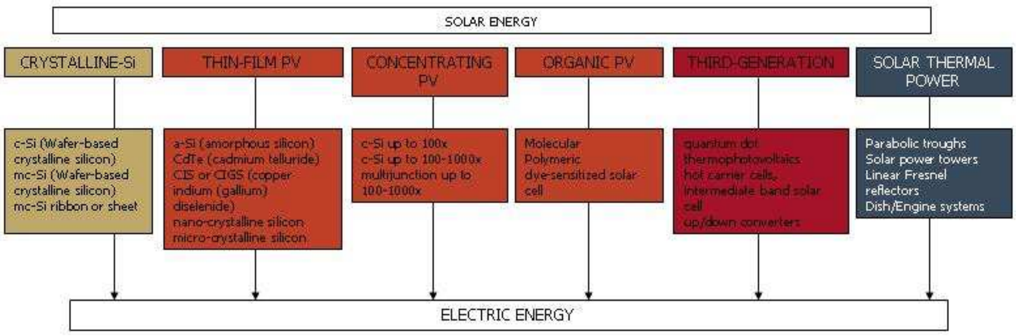

Figure 1: Solar technologies considered in the interviews with the experts

Solar photovoltaic

Solar energy can be directly converted into electricity through solid-state semiconductors, namely photovoltaic (PV) cells. Some technologies use natural solar intensity while “concentrating” technologies focus the direct component of solar radiation. Various PV technologies exist, all at different stages of development and maturity. First generation technologies are Crystalline-silicon PV, including large-grain poly- and single-crystalline materials, which represent 81% of worldwide solar installed capacity (SER, 2011; Bloem et al., 2010). These are fairly simple single-junction devices (diodes) whose maximum theoretical power conversion efficiency is limited by thermodynamic considerations to about 31% under direct AM1.5 sunlight (Ginley et al., 2008). Their efficiencies at research-scale have increased over the past years and are now close to the theoretical limit (Figure 2).

Second generation technologies are those that demonstrated practical conversion efficiencies and potentially lower costs per watt than Crystalline-silicon PV, but that have no significant market penetration yet. These include Thin-film PV, Concentrating PV and Organic PV and represent the remaining 19% of worldwide installed solar capacity.[2] Second generation technologies do not require the use of silicon wafer substrates, thus reducing the cost of manufacturing. The efficiency achieved in laboratory tests for these devices has also been increasing in the past years (Figure 2).

Among second generation technologies, concentrating PV is an emerging market with approximately 17 MW cumulative installed capacity at the end of 2008 (Bloem et al., 2010). High efficiency multi-junction solar cells can be used in combination with mirrors or lenses that concentrate solar light; typically the mechanics is complicated also by a sun-tracking system. The optic becomes extremely important in these applications and usually has a higher cost share than the cells (Ginley et al., 2008). While the market share of concentrating PV is still small, significant improvements could result from prototypes which are being produced and tested, from smaller (1-30kW) to larger (more than 100kW) applications (Kurtz, 2009).

Organic-based PV could potentially be produced at lower costs than first generation and all other second generation technologies. Organic PVs are fabricated from organic semiconductors, polymers and molecules that are relatively easy to produce. Even though their efficiencies have also been increasing, they are still low compared to those of Silicon-based PV (Figure 2).

Lastly, third generation solar technologies include innovative options such as hot carriers, multiple electron-hole pair creation and thermophotonics, which could potentially achieve very high efficiencies but are still at very immature stages of development.

Turning to the costs of PV modules, Figure 3 shows a significant variation within this technology. Costs have decreased in the last decades, going from about 22 USD/Wp in 1980 to about 2-5 USD/Wp in 2005 (Margolis, 2003; Shaheen et al., 2005). However, these costs are still high compared to those of other energy carriers. This hinders the diffusion of PV when no feed-in tariffs or other policy options are at work.

Indeed, cost reductions in the last decades can be for a larger part attributed to economies of scale and learning-by-doing which result from increased module production and capacity installed. These in turn were ignited by a number of supportive pricing policies, such as feed-in-tariffs in Germany or fiscal incentives for domestic PV installations provided by the Italian state. These favourable pricing rules have resulted in the growth of PV electricity at a rate of about 40% per year in the period 2000-2010. PV reached a time-averaged power production of about 2GW (IPCC, 2011).

[2] Cadmium telluride (9%), Amorphous silicon (8%) and Polycrystalline Thin films (2%) (SER, 2011).

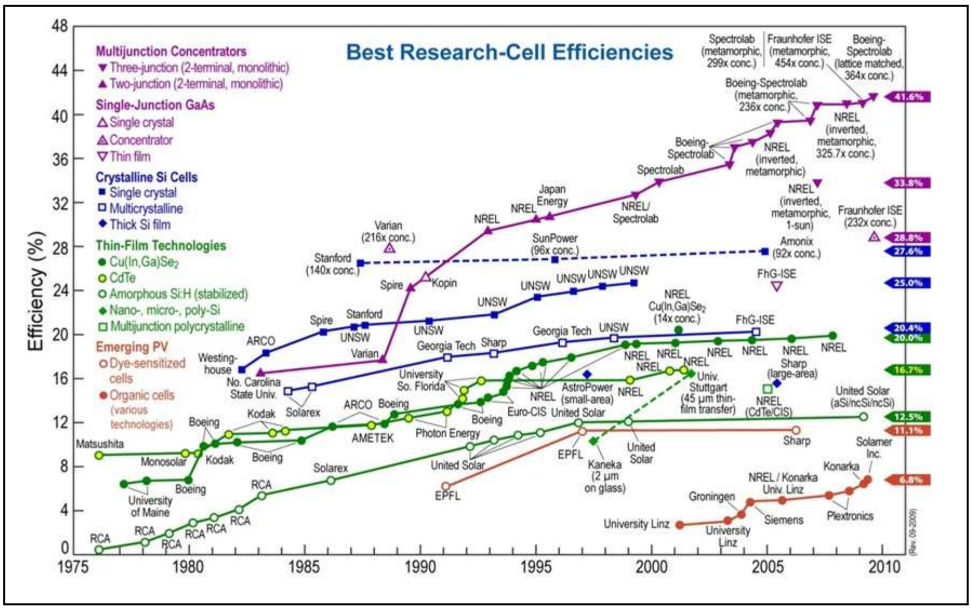

Figure 2: Performances of different solar cells

Source: Kazmerski, 2009. Production cell efficiency tends to lag the champion-cell figure by about two years.

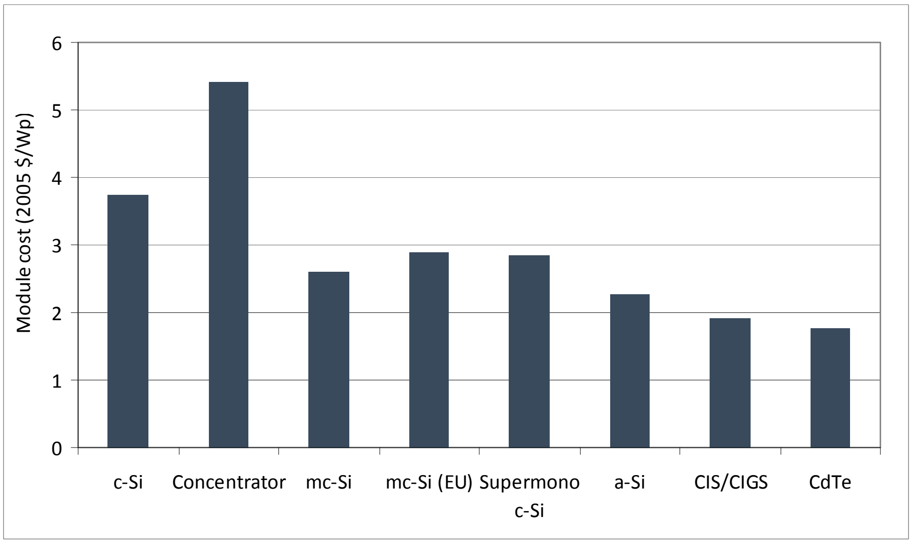

Figure 3: Costs in 2005USD per peak watt (Wp)

Sources: Greentech, 2009; EIA, 2007. Note that the module costs for concentrators are currently interested by large variations. Abbreviations: c-SI=Crystaline Silicon Single Crystallinge; Mc-Si: Globally vertically integrated multi crystaline silicon; Super c-Si: Supermono c-Si; a-Si: Thin-film amourphous silicon; CIS/CIGS: Thin-film copper indium gallium diselenide; Cd-Te: Thin-film Cadmium telluride.

While supportive policies are necessary to achieve GHG emission reductions in the EU, they represent costly options for policy makers. The technical improvement of solar technologies and their cost-competitiveness would lower the necessity to devote public funds to support deployment.[3]

Concentrated solar power

In CSP plants, mirrors are used to focus sunlight and to heat a working fluid. This high-temperature fluid is then used to spin a turbine or to power an engine that drives a generator, thus producing electricity. One of the main advantages of CSP plants is the possibility of storing the thermal energy captured from the sun: this allows decoupling the availability of electricity from that of sunlight. We surveyed experts on the most important CSP systems: Parabolic Troughs, Solar Power Towers, Fresnel Linear Reflectors and Dish/Engine Systems.

Parabolic Trough Systems concentrate the sun's energy through long rectangular curved mirrors; sunlight is focused on a tube (receiver) containing heating oil that transfers the thermal energy to a conventional steam cycle. Parabolic Troughs are the predominant CSP system currently in operation, with 500 MW of installed capacity representing roughly 91.5% of the 2009 worldwide CSP capacity (Greenpeace International, SolarPACES and ESTELA, 2010). Even though this technology is commercially proven and available, improvements are still needed, particularly with respect to the behaviour of the heat transfer media. The operating temperature potential has been tested at 400℃, at which steam quality is moderated, resulting in low efficiency of electricity production.

Power Tower Systems use a field of distributed mirrors that individually track the sun and focus the sunlight on the top of a tower. The concentration of sunlight enables to reach temperatures between 800 and 1000℃; these high temperatures can be used to produce steam or in hybridization with a combined-cycle fossil power plant. As a result the efficiency of Power Tower Systems is higher than that of Parabolic Troughs. Only 40MW based on Power Tower technologies are installed worldwide and wide scale commercial deployment has yet to come (Greenpeace International, SolarPACES and ESTELA, 2010).

Fresnel Linear Reflectors (FLR) are frontier technologies: in 2009 5MW were installed in one plant in Australia (Greenpeace International, SolarPACES and ESTELA, 2010). FLR rely on less expensive components than other CSP technologies: the mirrors are flat, rather than deeply curved, and located close to the ground, giving them lower wind profile (Denholm et al., 2010). This results in lower investment, operation and maintenance costs with respect to other CSP plants, but also implies lower system performance. As the technology is yet to be deployed, it is not clear whether low efficiencies will be outweighed by savings in capital, operation and maintenance costs.

Dish/Engine Systems are individual parabolic dishes in which a motor-generator (typically based on a Stirling Engine) is mounted at the focal point of the reflector. Prototypes that have operated over the last ten years were in the range of 10 to 100 kW of installed capacity per unit, for a total installed

[3] The efficiency (and as a consequence the economic viability) of solar energy technologies depends, in large part, on the quality of the local solar resource. In order to cancel out differences related to solar irradiance, during the interview we asked the experts to provide their estimates for a representative Mediterranean region.

capacity of 0.5MW (Greenpeace International, SolarPACES and ESTELA, 2010). This technology is well suited for decentralized power supply and stand-alone power systems and could potentially be scaled up to form arrays of higher overall capacity. However, these systems cannot be coupled with thermal storage and thus do not generate dispatchable electricity.

CSP is a particularly attractive option for electricity generation because it generally allows thermal storage and hybridisation possibilities. Investment costs are however still high and without policy intervention CSP is currently not cost-competitive with electricity production from fossil sources. For Parabolic Trough Systems, investment costs are 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). Investment, operation and maintenance costs of CSP technologies other than Parabolic Trough Systems are yet largely uncertain since demonstration plants have been built only recently. For example, in hand-built prototypes of Dish/Engine plants investment costs are estimated around 8.6 USD/W. These are expected to significantly decrease as manufacturing capacity increases (Denholm et al., 2010; Mills, 2004).

Similarly to the PV case, the production of electricity from CSP installations has grown fast in recent years and reached a cumulative installed capacity of about 1 GW in early 2010 (IEA, 2010c). Considering the new projects under development (e.g. in China, India, Morocco, Spain and the United States), the global stock of CSP plants is expected to reach a total 15 GW (IEA, 2010c).

The potential for cost reductions in CSP technologies lies in improvements of optical materials (solar collectors, receivers, concentrators, reflectors, optical coating for mirrors) and heat-transfer/storage fluids (working fluids that are stable over a broad temperatures range) (Denholm et al., 2010; Mehos, 2008). These improvements are generally aimed at achieving higher temperatures in the working fluid, thus leading to greater efficiencies in the production of electricity. Finally, large scale deployment should lead to (1) the reduction of both capital and operation and maintenance costs through learning from experience and (2) economies of scale in larger plants.

Role for RD&D investments

Significant RD&D investment will be required in the next decades to foster technological improvements in both PV and CSP technologies, and to promote learning-by-doing effects as well as economies of scale resulting from large scale production.

EU Public RD&D investment in PV and CSP technologies since 1980 averaged 163 million USD per year (Figure 4). With the exception of a peak in 1984, public investment has been rather stable until the beginning of 2000, with a minimum of 114 million USD in 1999. In recent years, public EU RD&D spending has shown an increasing trend (around 209 million Euros for 2007). This was the result of the general increase of oil and gas prices and climate change concerns: indeed, renewable energy options could jointly address climate change challenges and energy issues, decoupling economic growth from fossil fuel use. The recent economic crisis has slowed down the most recent numbers, hence for the purpose of our analysis we asked experts to consider the 2004-2009 average expenditure in order to smooth out year-specific idiosyncrasies.

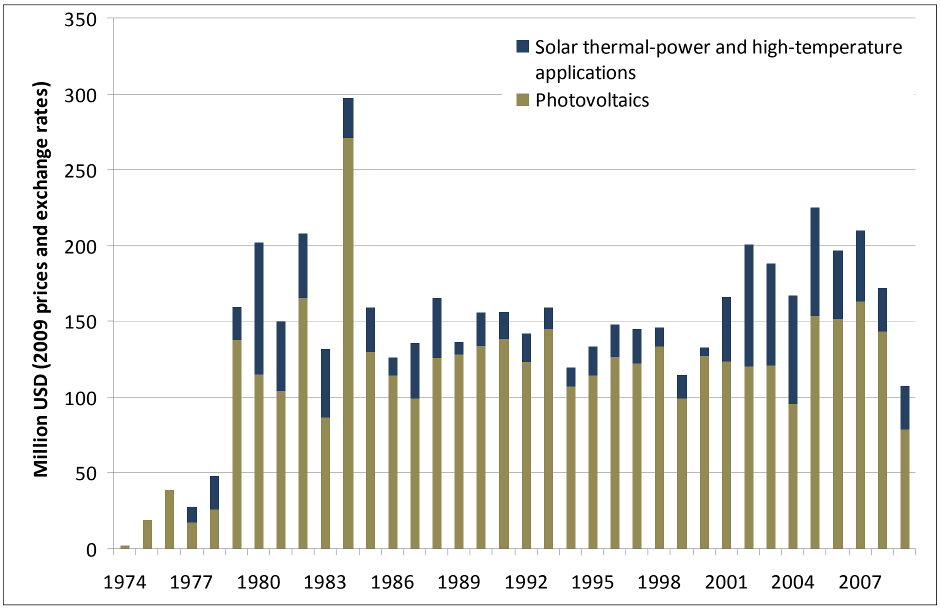

Figure 4: Trend of public RD&D investment in solar technologies by EU countries, 1978-2008

Source: IEA, 2011.

Germany, France, Italy and Spain have the four highest RD&D budgets for PV in Europe, while public investment for CSP is concentrated in Spain and Germany. EU public investment in 2007 represented 55% of the OECD investment in PV technologies, while the USA and Korea follow, accounting for 30% and 8%, respectively. EU and US public investment in CSP in 2007 represented 71% and 25% of total OECD investment, respectively (IEA 2011).

Public RD&D investments are however only a fraction of the RD&D effort in any given country. Private RD&D investments in renewable technology are largely unknown, since no country statistics are publicly available. A recent analysis of the JRC for the EU (EC, 2009) shows that in 2007 private contributions are estimated around 60% of the total RD&D investments in PV and CSP technologies (see Figure 5 for estimated RD&D investments in PV and CSP from industry and public sectors for European IEA Member Countries and the EU). The little available evidence also shows that private investments are expanding rapidly. In particular, solar energy led all clean energy technologies in terms of venture capital investments in 2008, with 5.45 billion USD of investment and 88% growth from 2007 (Bloomberg, 2009).

As private RD&D numbers are elusive, a proxy for innovative activity in different countries that is commonly adopted is the count of patents in solar technologies. On this basis, Dechezleprêtre et al. (2010) ranked Japan, USA, and Germany as the top innovators for solar PV worldwide. Haščič et al. (2010) show that patenting in PV technologies worldwide exhibited particularly rapid growth in recent years, with China and India being respectively the 10th and 16th top innovator in PV technologies. Patents in PV technologies in 2000 were about eight times higher than at the end of the 1980s. In addition, the transfer of PV technologies between Annex I and non-Annex I countries is significant. Using patent protection in foreign countries as a proxy of technology transfer, one can show that between 1978 and 2007 more than 4,800 patents were transferred from the 13 top innovator countries in PV technologies to the 13 top receiving non-Annex I countries (Haščič et al., 2010).[4] Japan, the US and Germany are the top exporters of technologies, while China represents the top market for foreign PV technology protection among receiving countries.

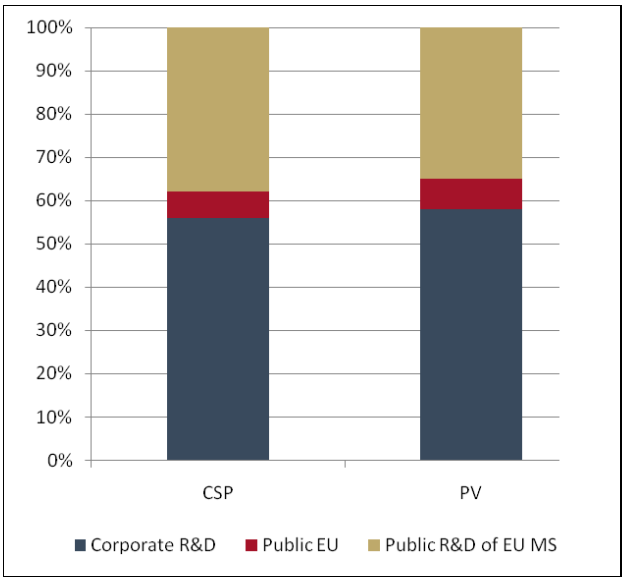

Figure 5: Estimated RD&D investment in PV and CSP from industry and public sectors for European Member Countries and the EU

Source: EC, 2009.

Role for policy

In the past decades, renewable energy policies have come to the forefront of the debate surrounding climate change and energy security. The interplay between innovation levels, cost reductions and policy in support of solar energy production is shown in Figure 6. On the left axis of the graph we count the number of policies that were implemented in each EU country and that specifically mentioned support for solar (or more generally for renewable) technologies over the period 1978-2010 (IEA, 2010e). These policies range from feed-in tariffs and tax exemptions to command and control standards. RD&D-related policies represent only 7% of the total policies supporting solar and renewable energy. On the right axis, we measure the production of electricity (GWh, logarithmic scale) in PV and CSP technologies in 2008 (IEA, 2010a). As expected, countries that implemented more policies in support of solar and renewable technologies displayed higher electricity production from solar sources than countries where policy activities were lower. Policies, even though not directly financing RD&D, have also been inducing innovation, both measured in terms of private RD&D investments and in terms of patents. Top innovating

[4] If a country patents the same technology abroad twice (in two different countries), the patent is counted twice.

countries in solar technologies, such as Germany, Spain, Italy and France are those countries with the highest number of policies in support of solar electricity production.

While gauging how public and private RD&D investments will affect technology costs and the resulting diffusion of solar technologies, it should be kept in mind that specific policy interventions will play a crucial role. First, policy supporting solar technologies can provide incentives for diffusion even if technologies are just cost-competitive, but not cheaper, than traditional options. Second, policy can help to overcome important barriers to diffusion that are not necessarily linked to costs (see Section 6).

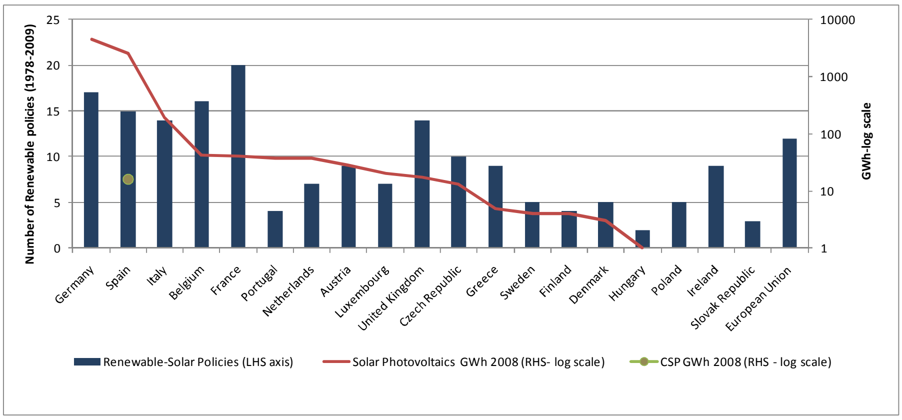

Figure 6: Policies supporting solar energy (1978-2009) and PV and CSP electricity production (2008) in IEA Member States

Sources: IEA, 2010a; IEA, 2010e.

3. Expert elicitation

Expert elicitation (EE) is the process of gathering the judgment of experts through specially designed methods of verbal or written communication. EE processes are increasingly applied to different research fields to deal with complex phenomena characterized by uncertainty and lack of data. The literature on decision analysis provides interesting theories on the techniques that should be applied to elicit expert judgments under uncertainty, as is the case for energy projections (Morgan and Keith, 2008), climate change impacts and policy analysis (Morgan and Keith, 1995; Morgan et al., 2001), and environmental policy in general (Morgan and Henrion, 1990).

Applications to clean energy technologies started only recently. Expert elicitation processes used to assess the potential of success of carbon-free technologies are relatively scarce, but provide important insights for our analysis. Baker and Peng (2011) calculate the Expected Value of Better Information (EVBI) gained through the use of expert elicitations in order to better assess energy technology RD&D portfolios. They estimate that the EVBI ranges from 100 million to 11 billion USD for individual technology categories. Baker et al. (2009b), Baker and Keisler (2011), Chan et al. (2010), Baker et al. (2009a) and Curtright et al. (2008) use expert elicitation to investigate the uncertain effects of RD&D investments on the prospect of success of carbon capture and storage, hybrid electric vehicles, cellulosic biofuels, and solar PV technologies. Our study is particularly related to the latter two where expert judgments are used to assess the role of RD&D investments to support technical change in PV technologies and, as a consequence, the potential of technical change with respect to impacting the cost of carbon emissions reduction.

The literature on decision analysis and psychology warns that, 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 'bias' refers to a skewing of the expert's estimate from some reference point and can be of different nature. In presence of uncertainty, for example, people often anchor their response to the ease with which they can imagine an event occurring or to some "central" value. These as well as other biases may introduce an underestimation of the probability of extreme events and can negatively interfere with the elicitation process.

To minimize such bias in experts' estimates, we chose to gather expert estimates by applying specially designed questions and methods of communication (Morgan and Henrion, 1990; Meyer and Booker, 1991; O'Hagan et al., 2006). The survey was therefore tailored considering the complexity of the analysis, the presence of multiple interests and perspectives and the need to account for the uncertainty characterizing technological development.

We identified and selected a mix of experts with strong scientific backgrounds and sound empirical knowledge. We looked for a balanced group of experts who could represent the major perspectives and fields of knowledge (engineers, economists, policy makers). We specifically made the choice of interviewing experts from heterogeneous backgrounds: academia, institutions and private sector are represented in a balanced way to ensure a thorough analysis of the topics. The level of expertise of each selected interviewee was carefully assessed considering tangible evidence such as publications and direct involvement in projects related to research and development of solar technologies.

Figure 7 summarizes the geographical distribution of the experts who took part in our survey and their institutional belonging (see Table 1 for the full list of experts). We also took into account the experts' availability and willingness to participate, and their impartiality and lack of an economic or personal stake in the potential findings. The quality and level of expertise was further explored and confirmed by an exercise of self-evaluation with respect to each of the selected technologies, using a 1 to 5 scale, from low to high expertise.

To test the questionnaires and the elicitation process, we carried out few pilot interviews with experts from the academia and the private sector. This process was crucial to refine and condense the various sections of the questionnaire.

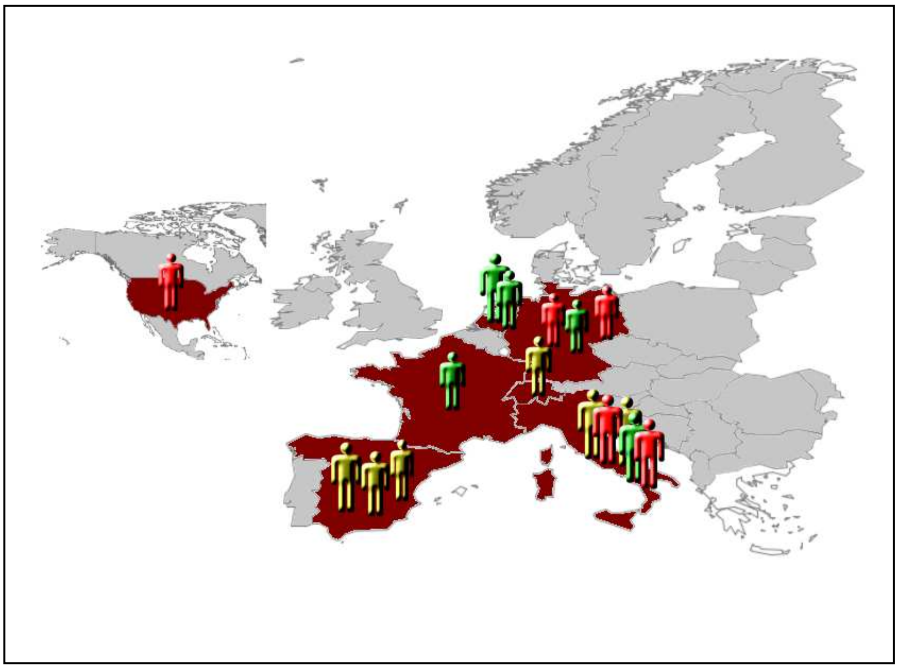

Figure 7: Origin of the experts and professional sectors of belonging

Colours indicate professional sectors: green = institution, yellow = academy, red = private.

Composition of the expert pool

Figure 8 compares the level of expertise in the 6 solar technologies considered by using the output of the self-evaluation exercise included in the survey. More specifically, the graph shows the distribution of the experts with respect to their level of specialization in any specific solar technologies and to their degree of knowledge of several technologies.[5]

Most of the experts selected have a high degree of specialisation (Specialization Index > 50%) whereas the wide spread along the X axis suggests heterogeneous levels of knowledge with respect to the different solar technologies (Coverage Index). The experts' background partially influences their specialisation and coverage: all the experts from the private sector are highly specialised, three out of five experts from the international institutions show high coverage of solar technologies knowledge (Coverage Index >50%).

Most experts (Figure 9) 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.

[5] The scatterplot area can be read as follows: (i) the high/left quadrant, identifies experts with low values of coverage and high level of specialisation, (ii) the high/right quadrant, includes 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.

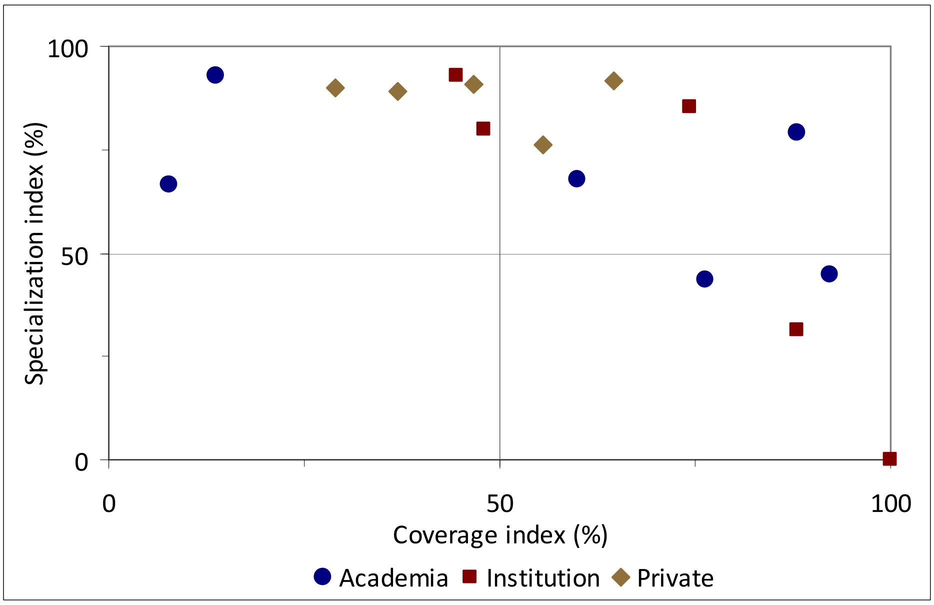

Figure 8: Ordering of the experts based on the Coverage Index and the Specialisation Index

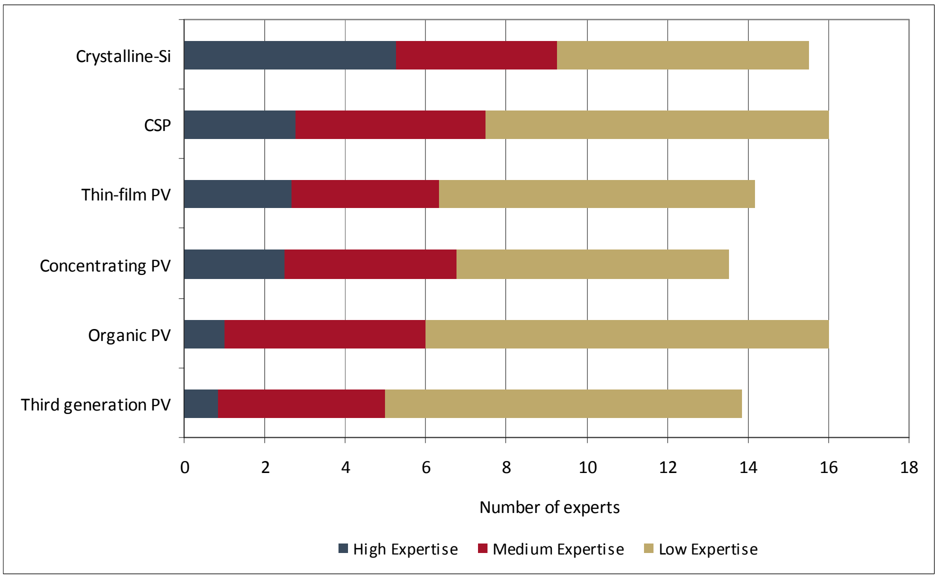

Figure 9: Distribution of the experts with respect to six major classes of solar technologies

High expertise: max level of knowledge >3; medium expertise: max level of knowledge =3; Low expertise: max level of knowledge <3.

4. Technical potential of solar technologies

To identify the most important drivers of variations in the costs of PV and CSP, the survey asked each expert to comment on the current level of technical development of the proposed technological options. The experts provided insights on the level of maturity of each technology and on the specific conditions that would lead to cost competitiveness and to commercial success with respect to traditional fossil fuel technologies for electricity production. They were also asked to identify the main bottlenecks that currently represent barriers to cost reductions and to specify what type of RD&D would be most needed. Table 2 reports keywords that were mentioned by at least four experts when discussing barriers and issues connected to each of the technological options. In particular, organic PV attracted very diverse comments and consensus across experts on what the problems are and what is needed.

Table 2: Keywords mentioned by at least 4 experts

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

Main advances in Crystalline-silicon technology need to come 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),[6] reducing the large gap between laboratory efficiency and module efficiency. In general, all the experts are convinced that in Crystalline-silicon technology there is room for significant technical improvements which would result from a structured demonstration activity.

The crucial improvements seen as necessary for the success of Thin-film technology relate to module efficiency (which would reach 15-18%), material toxicity and to the development of large-scale production units, which would lead to economies of scale. The durability of installations should be proven through specific demonstration tests.

Advances in Concentrating PV technologies would result only from an integrated effort in both basic and applied R&D and demonstration activities. As the systems are fairly complex and costly, effort should work in increasing precision and stability at lower costs.

Organic PV and Third generation PV technologies were judged to need significant further development. For Organic PV, major improvements are needed with respect to understanding materials’ properties and ensuring stability and efficiency of the installations. Third Generation technologies, where innovative materials and devices are being processed at the nanoscale, are still at the exploration phase. Structured demonstration projects should be carried out to assess the potential and functionality of these technologies.

In the case of concentrating solar power, main barriers to development are heat storage and durability.

[6] For abbreviations, see notes to Figure 3.

Given the current status of development, each expert was asked to allocate 100 "chips" (representing the current annual level of public RD&D investments, or approximately 163 million USD)[7] to the different solar technologies considered in the survey. Several experts indicated that in the next twenty years the largest share of the RD&D budget for solar energy technologies should be devoted to improving "mature" technologies (see the aggregate budget allocation in Figure 10) such as Crystalline-silicon PV, Thin-film PV and CSP. Applied R&D and demonstration play the biggest role for these technologies, as experts uniformly perceived the need to work in "outside the lab" conditions to test real efficiency, to improve lifetime and to bring down costs via learning-by-doing processes. All experts indicated explicitly that funding for Demonstration (as opposed to basic Research and Development) should be a consistent and crucial part of public investment (Figure 10). This is in sharp 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 (CSP) went to demonstration activities (EC, 2009).

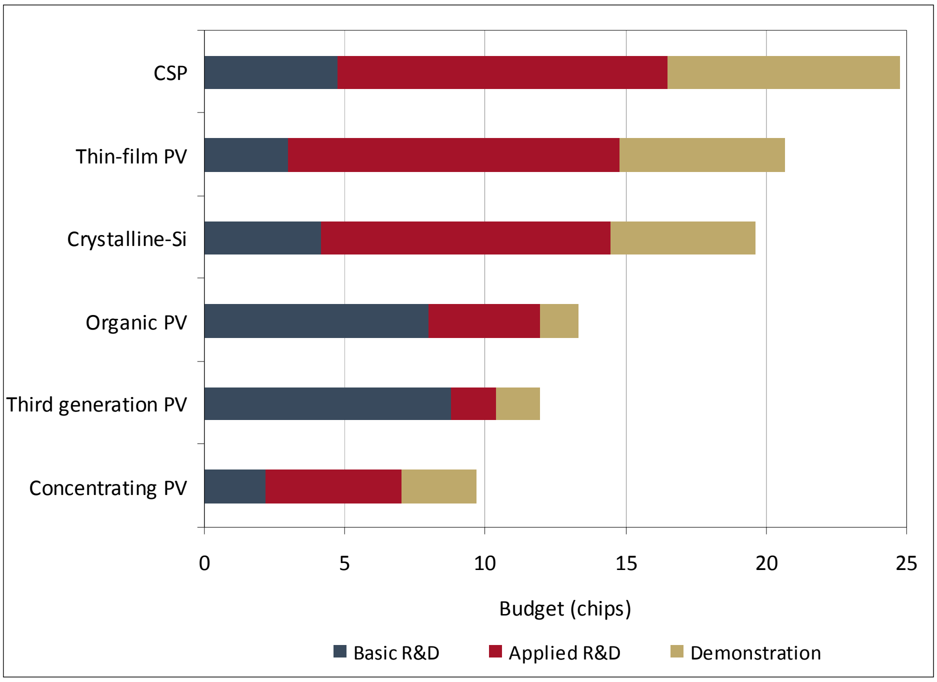

Figure 10: Aggregate allocation of the RD&D budget and type of RD&D - 2010-2030

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 technology options (Figure 11). A fairly uniform low amount of chips was allocated to Concentrating PV and Third Generation PV (on average 9.7 to Concentrating PV and 12 to Third Generation PV). These are technologies that most experts see as promising and constant efforts should be made to identify their true market potential. Organic PV is more controversial: it received on average a larger amount of chips (13.3) but with larger fluctuations across experts, reflecting the

[7] See Figure 4.

heterogeneity of experts' views with respect to this technology. Most experts consistently allocated a relatively larger part of their budget to what most consider a promising and relatively stable technology such as Thin-film PV (on average 20.7 chips). Other more mature technologies, such as Crystalline-silicon PV and CSP, received on average larger shares of the total budget, but with much wider lower and upper bounds, indicating a more heterogeneous distribution among the experts. In these latter cases, the choice to allocate a higher budget to a specific technology mostly reflected the area of expertise of each expert (see also Figure 12 and relative discussion).

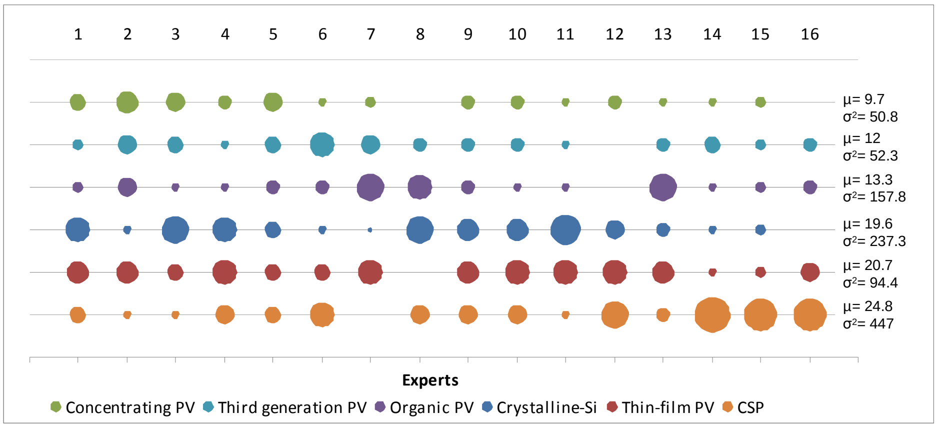

Figure 11: Budget allocation among the different technology options

For each technology (row) both the average (μ) and variance (σ) in the chips allocated is given. For each expert (column) the total of chips allocated is 100.

Sensitivity analysis on experts' budget allocation

The experts' decision on the distribution of the allocated budget could be biased towards those technologies which are the main focus of the expert's research or policy activity. Figure 12 tests for the independence of the experts' budget distributions with respect to their area of focus by relating the share of budget per technology to the level of experts' specialization. For each expert we report the maximum allocated fund and the level of expertise in the corresponding technology. We also provide reference levels dividing the *x*-axis: the "equidistribution" line is associated with 16.7 chips - the level of investment that each technology option would have received assuming that the budget was equally split between the 6 technologies; the "2-equidistribution" line, which represents 33.4 chips - twice the equal distribution value.

Experts who allocated a budget higher than 33.4 chips to more than one technology are reported more than once. We also provide information on the background of the expert (academia, public institutions or private sector). What emerges from Figure 12 is that all experts but one allocated a higher budget to technologies they know better. This is particularly pronounced for experts from the private sector and in general represents a natural bias towards one's focus of research. Two reasons can explain the experts' choices in this regard. First, due to their deep knowledge of the subject, the experts might be confident that higher investments in the selected technology would lead to faster or greater results. Second, the experts might also be aware of the limits of the technology; allocating more funds might be a way to overcome these shortcomings. The exercise demonstrates the importance of selecting top-experts of each technological option in order to guarantee a robust expert elicitation process.

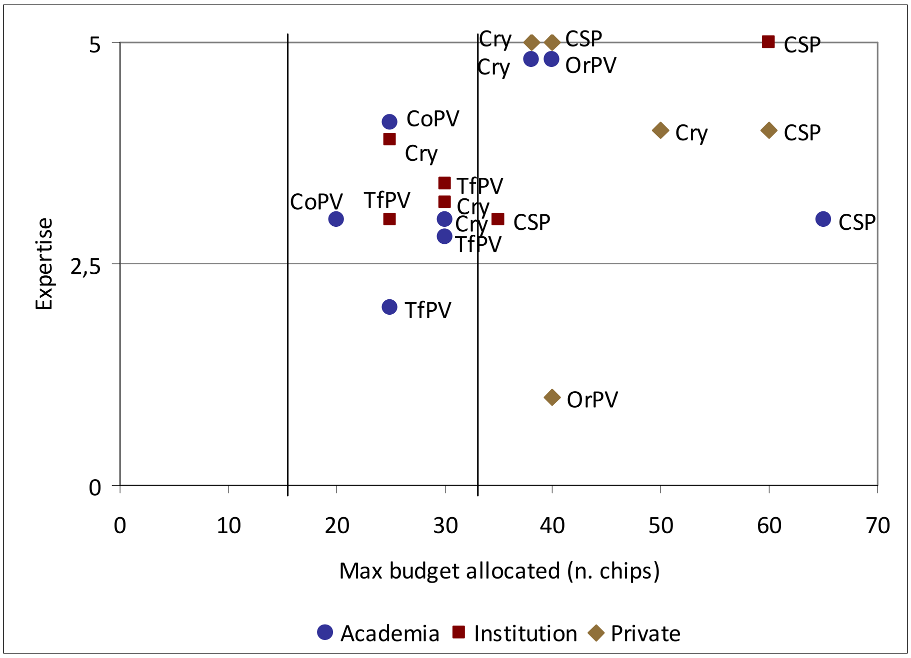

Figure 12: Maximum budget value allocated and related expertise level expressed for given technology.

Cry: Crystalline-Silicon; TfPV: Thin-film PV; CoPV: Concentrating PV; OrPV: Organic PV; CSP: Concentrated Solar Power.

5. RD&D and future costs

The core aim of the survey was to assess if and under what conditions the costs of solar generated electricity would eventually become competitive with other power technologies. To this end, we directly asked the experts to estimate the 10^{th}, 50^{th} and 90^{th} percentile of expected cost of solar electricity in 2030 under different RD&D investment scenarios, with the 50^{th} percentile representing the most likely value. In addition, we also asked experts to evaluate the likelihood of costs being below given representative thresholds.[8]

Since experts typically think in terms of technological endpoints and not in terms of electricity costs, we provided them with a formula deriving the cost of electricity from Solar PV or CSP from specific technical factors, such as technology efficiency, lifetime, module areal cost, balance of system cost, peak insulation power, and discount rate (see Annex II for the complete formula). Experts who did not feel at ease with directly providing monetary

[8] 56% of the experts considered the evolution of electricity costs in the EU only, while 44% referred to global conditions, arguing that the market for this technology is global and lower costs would diffuse fairly rapidly.

estimates were free to use the formula to estimate how improvements in technical factors would result in lower monetary costs.[9]

The estimates of the 2030 cost were collected conditional on three alternative scenarios of public EU funding to RD&D. The first scenario assumed that the current annual EU public RD&D level of investment as a share of GDP would be maintained throughout 2030 (182 million of USD,[10] Scenario Current RD&D). The second scenario assumed an immediate 50% increase of public EU RD&D investment, then sustained until 2030 (Scenario +50% RD&D). In the third scenario, annual public EU RD&D would scale up to twice the current levels and be maintained there up to 2030 (Scenario +50% RD&D). We asked the experts to provide cost estimates assuming that annual expenditure would be constant between 2011 and 2030. This is in sharp contrast with the significant oscillations experienced by EU countries in the last 20 years (see Figure 4).

Experts' estimates of the expected cost of electricity in 2030 are reported in Figure 13. Each segment represents the 50th, 10th and 90th percentiles under current levels of EU RD&D funding, in black, and under the +50% and +100% RD&D scenarios, in dark and light grey, respectively. Experts 13, 14, 15 and 16 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. Expert 2 specifically considered concentrating PV technologies only, which is a frontier technology associated with higher costs. Hence in some of the aggregated figures we explicitly exclude Expert 2.

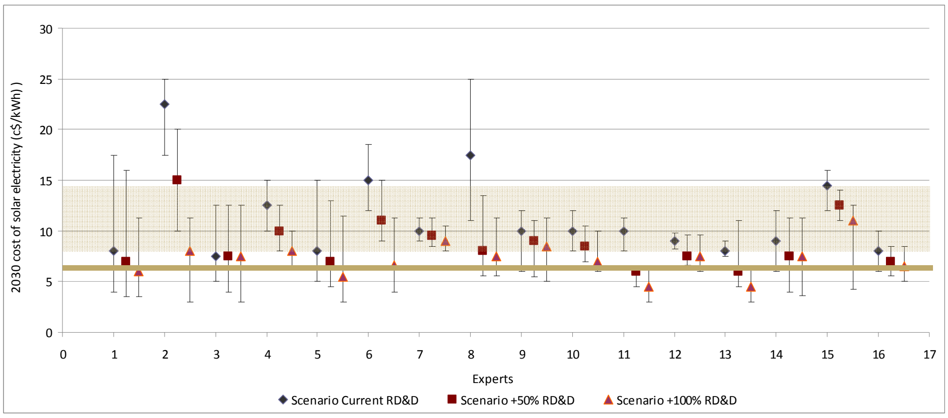

Figure 13: Estimates of 2030 solar electricity costs (50th, 90th and 10th percentiles) under different EU RD&D funding scenarios

Current RD&D: black. 50% increase in RD&D: dark grey, 100% increase in RD&D: lighter grey. Experts 13-16 provided cost estimates for CSP technologies, while the rest considered PV technologies. The shaded area defines the 2020 range of expected cost of electricity produced from PV: from 7.3 cUSD/kWh in (Breyer et al. 2009) to 14.5 cUSD/kWh (IEA, 2010d). The green area represents the 2020 US Department of Energy goals for CSP as reported in (IPCC, 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, 2010c).

[9] As already mentioned, since the efficiency of solar technologies depends on insolation, during the interviews we referred to a representative southern European region. However, two experts clearly referred to northern Europe insolation values.
[10] We asked the experts to evaluate the average yearly expenditure over the period 2004-2009 in order to smooth out the recent slowdown in investments due to the economic crisis. Numbers were presented both in Euros and Dollars.

Assuming the current RD&D scenario, most best guesses lay within the 7.5 - 14.5 cUSD/kWh range. This is in line with estimates reported in the IPCC Report (2011) which are represented by the shaded area in Figure 13. The average expected cost resulting from the expert estimates is 11.7 cUSD/kWh,[11] while it falls to 10.8 cUSD/kWh when Expert 2 is left out of the sample. The average expected cost for CSP only technologies is 10.1 cUSD/kWh. This value is well above the green shaded area in Figure 13 representing the 2020 US Department of Energy goals for CSP as reported in IPCC (2011) and more in line with the 2030 cost projections from IEA, which range from 10.7 to 15.6 cUSD/kWh (IEA, 2010c).

When public EU RD&D funding is assumed to be 50% higher than current levels the estimated costs are on average 20% lower: the majority of best guesses in this case ranges from 7 to 11 cUSD/kWh and the average expected cost is 9.3 cUSD/kWh,[12] while for CSP the average expected cost is in this case 8.9 cUSD/kWh.

The estimates of the evolution of solar electricity costs conditional on RD&D investments provided by eight out of the sixteen experts suggest increasing returns to scale to RD&D,[13] as the marginal improvement of the +100% RD&D scenario is higher than that of the + 50% scenario. The average expected cost conditional on a 100% increase of public RD&D funding is 7.7 cUSD/kWh, with most best-guesses ranging from 6 to 9 cUSD/kWh. Conversely, all experts concentrating mainly on CSP solar technologies provide estimates suggesting decreasing returns to scale: a +100% RD&D scenario implies an average expected cost of 8.1 cUSD/kWh.

All experts agree on the direction of the effect of RD&D on expected costs, namely that higher RD&D expenditures lead to lower average expected costs. However, their opinions vary widely with respect to the effect of RD&D on the uncertainty, which we measure using the difference between the 10th and the 90th percentile in the cost estimates (see Figure 14).

According to six out of sixteen experts, increasing RD&D by 50% reduces the uncertainty surrounding costs (+50% scenario). However, increasing public funding further (+100% scenario) results in higher uncertainty. Moreover, twelve experts provided wider cost ranges for at least one of the two higher-than-current RD&D scenarios, indicating a generally higher degree of uncertainty in evaluating departures from the *status quo*. This, as explained by some of the experts, depends on the fact that a 100% growth in the solar RD&D budget would probably result in higher investments in less mature technologies, whose success has a higher degree of uncertainty than for more mature technologies.

[11] Expected costs are calculated using all the information collected: those regarding direct elicitation of costs and those collected asking likelihood of costs being below thresholds that we discuss later in this section.
[12] Leaving out expert 2 does not significantly change the average expected cost figure: under the +50% RD&D scenario divergence across experts is extremely reduced.
[13] Increasing returns to R&D have been postulated on the assumption that larger firms are more research-efficient and that ideas/blueprints can be used repeatedly without additional cost.

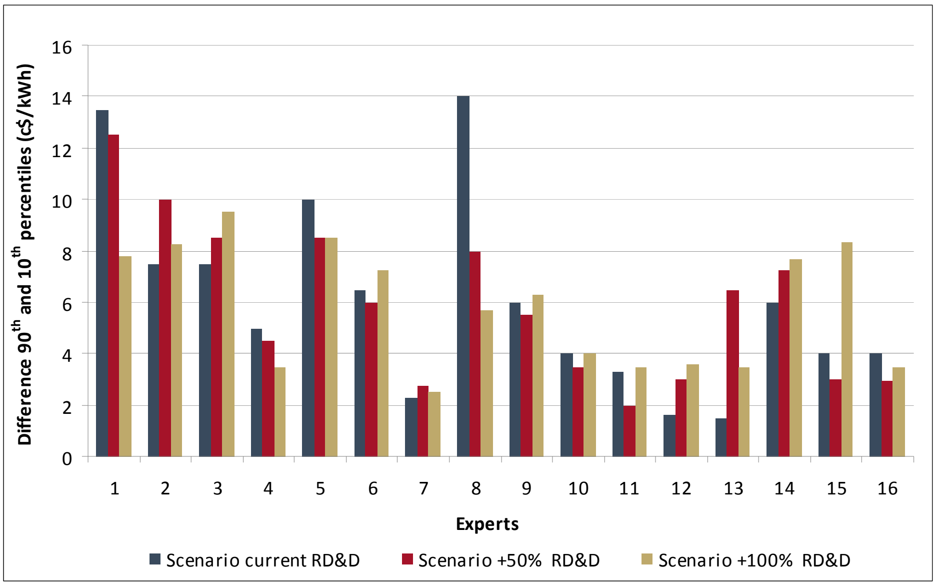

Figure 14: Uncertainty in experts' cost estimates

Uncertainty is measured as the difference between the 90^{th} and 10^{th} percentiles in each expert's estimate of 2030 cost under each of the three RD&D funding scenarios.

To check the consistency of the experts' responses, we also asked each expert to estimate the probability that the cost of solar electricity in 2030 would be lower than some representative threshold, conditional on the same alternative RD&D investment scenarios outlined above. The three different "breakthrough" cost levels proposed to experts 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 CO_2 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 mild stabilisation target (leading to a 550ppm CO_2 only stabilization target by 2100). 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.[14]

Asking experts the follow up question on the likelihood of reaching cost targets allowed us to control the risks linked to the direct elicitation of subjective probabilities,[15] to increase the amount of elicited information, and to deepen the discussion with the expert, hence improving our perception of the experts' beliefs. In cases where the two answers were inconsistent, we

[14] Baker et al. (2009a).
[15] One of the main risks is the possibility to collect highly context-dependent answers which do not represent a true, mathematical, probability measure (Meyer and Booker, 1991). Examples of distortion in the elicited probabilities are: treating low-probability events as impossible; overconfidence and other anchoring effects; overweighting salient events (O'Hagan et al, 2006).

engaged the experts in follow-up questions to verify what the true estimate was.

If the current RD&D expenditures are constant through 2030, the average expected cost estimate is above the highest threshold of 11.27 cUSD/kWh, and the probability of reaching a breakthrough is around 66%. As discussed above, excluding Expert 2, who was focussing on a single specific high cost technology, the average expected estimate falls below the price of electricity produced with fossil fuels in presence of the carbon tax and the average probability of solar technologies being cost competitive 71%.

A 50% increase in the RD&D funding leads to a significant increase in the probability of abating the costs below the 11.27 cUSD/kWh threshold by 2030: the average probability of breakthrough increases from 66% to 78%. Under the +100% scenario, all but one expert agree that the cost of solar electricity would be lower than 11.27 cUSD/kWh, with a probability of breakthrough higher than 90%.

All experts agree that under the current RD&D scenario reaching either the 5.55 cUSD/kWh or the 3 cUSD/kWh target is very unlikely (<10% probability). The picture doesn't change substantially when RD&D investment increases by either 50% or 100%. According to most experts, increasing the RD&D budget by 50% (100%, respectively) would increase from 5% to 12% (21%) the average probability of reaching 5.55 cUSD/kWh.

Combining information on both the percentile cost estimates and the elicited probabilities associated with the three cost levels, we derived the probability distribution function of 2030 solar electricity costs for each expert. Figure 15 plots the 2030 expected cost under the current RD&D scenario (*y*-axes) and the % decrease in the 2030 expected cost (*x*-axes) under the +50% and +100% scenarios (in blue and red, respectively) for each expert.

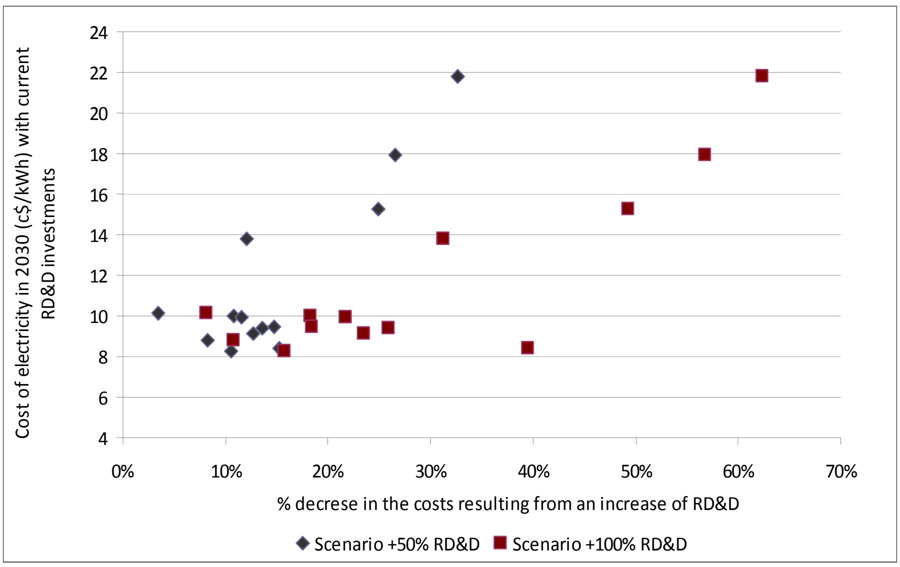

Figure 15: Expected costs of electricity in 2030 under the current RD&D scenario (y-axis) and % decrease in the 2030 expected cost under the additional RD&D funding (x-axis)

+50% RD&D scenario: blue; +100% RD&D scenario: red. The three experts for which follow up questions to ensure consistence across answers were not possible are left out of the sample.

Experts appear to be clustered around two alternative visions, based on their estimates under the current RD&D scenario. The first cluster, encompassing 70% of the experts, is scattered around a cost of 9 cUSD/kWh. This group of experts is more optimistic with respect to the 2030 cost figures under current RD&D. The remaining experts' estimates can be grouped around a cost of 16 cUSD/kWh. This second cluster of experts share larger expectations on the effectiveness of increasing RD&D above current levels. Experts that expressly considered CSP technologies are equally divided across the two clusters.

Increasing RD&D investments results in the convergence of the two clusters, with an almost complete overlap under the +100% RD&D scenario. In this case, the variance of expected costs is reduced by one order of magnitude with respect to the current RD&D scenario case: the average expected cost under the +100% RD&D scenario is 7.2 cUSD/kWh, with a 1.1 cUSD/kWh variance. Conversely, under the current scenario measured including (excluding) Expert 2 the variance is 18 cUSD/kWh (10 cUSD/kWh). This suggests that larger RD&D programs in solar technologies do not necessarily decrease the future uncertainty each expert attaches to his/her own estimates, but do smooth out differences across experts.

The estimates of the EU experts surveyed in this study are in general more optimistic and less dispersed than those of the US experts engaged in the expert elicitation survey by Curtright et al. (2008), although any real comparison is not possible as the two studies differ in the range of costs over which the questions focussed. All US experts reported a probability >70% that under specific assumptions[16] the 2030 cost of at least one of the different PV technologies analysed would be below 24 cUSD/kWh. Half of the surveyed experts attach a greater than 50% probability to the event that the cost could eventually go down to 6 cUSD/kWh before 2050.

Baker et al. (2009a) surveyed US experts in second generation PV technologies. By assessing the evolution of specific technical endpoints,[17] they collect (very disperse) probabilities associated to the 2050 costs of electricity being below 5 cUSD/kWh ranging between 0 and 40%.

6. Diffusion of solar technology

The potential for success of solar PV and CSP technologies cannot be assessed simply based on the level of technical barriers and development and on the cost-reducing potential of RD&D programs. Although the availability of low-cost solar technology is a key requirement, it is through the worldwide diffusion of these technologies that greenhouse gases emissions will be impacted. In this respect, even if solar technologies were mature and

[16] 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.

[17] 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.

efficient from a technical point of view, non-technical issues and barriers could still play a role in slowing their worldwide diffusion.

The fourth section of the survey addresses precisely this point. First, we asked experts to indicate which geographical area of the world had the highest probability of being the first to reach commercial success in solar technologies (Figure 16). 35% of the experts indicated that the breakthrough in solar technologies will take place in the EU, while 29% believe China will be the first country in which solar technologies will achieve cost-competitiveness. Further, 23% and 13% of the experts believe that success will take place in the United States and Japan, respectively.

While interpreting this result, one should keep in mind that the pool of experts we selected was European. As a result, the indication that Europe has the highest probability of reaching the breakthrough in solar technologies could be partly biased by the origins of the experts. More likely, though, the experts' responses reflect the presence in Europe of factors both pulling the demand for and pushing the supply of solar electricity. These factors affect innovation decisions and have fostered and will sustain the European leadership in solar technologies. As already noted in Section 2, public investment in solar technologies is higher in the EU than in the USA, indicating the great collective effort of Member States in developing cost competitive solar technologies. Moreover, experts' opinions on this issue possibly incorporate the presence of clear political support and specific policies that favour renewable energy penetration at the European level. Such policies are key factors to ensure that currently available technologies exit the so-called "valley of death" of demonstration and deployment.

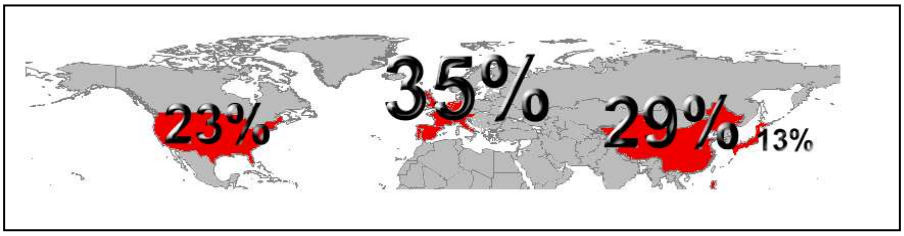

Figure 16: Countries' probability of being the first to reach the commercial breakthrough in solar technology

The experts also commented on how national RD&D programs should be shaped as a result of the specific nature of knowledge flows between countries with respect to solar technologies. 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 RD&D program to develop absorptive capacity and therefore to be ready to adopt breakthrough technologies eventually developed abroad.

Figure 17 summarizes the six non-technical barriers that the all experts identify as the most likely to set back the widespread diffusion of solar technologies. These include long-lived capital stock of currently used fossil fuel plants for electricity production, the intermittency of solar power sources, geographical constraints linked to insolation levels and land availability, unfavourable pricing rules, and rare metal supply (such as tellurium).

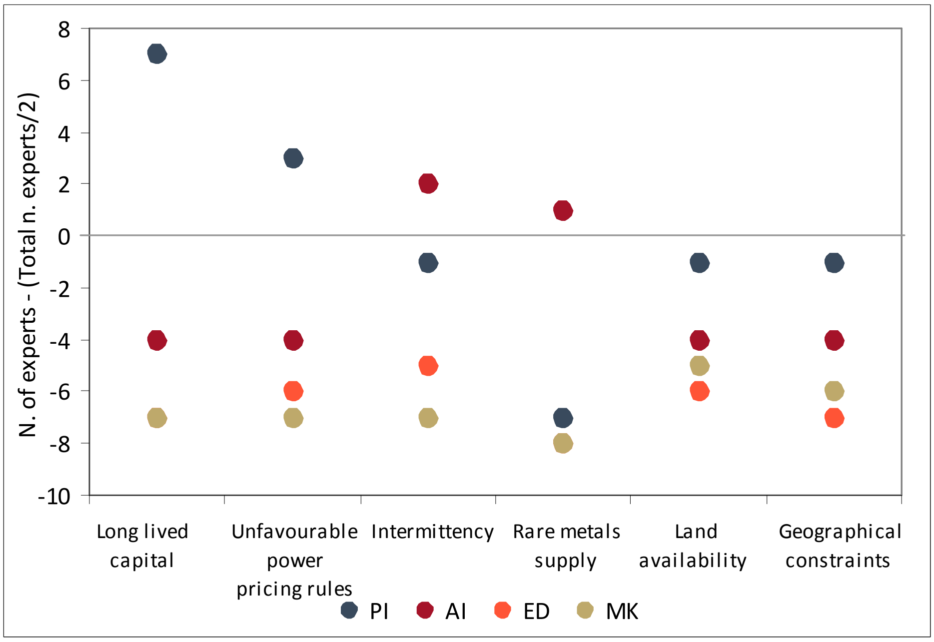

Figure 17: Non-technical barriers to the diffusion of solar technologies and potential solutions to overcome the barriers

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 of the solutions which collected fewer votes from the experts.

First, past capital investments in fossil power plants make it hard to switch to a new technology unless the plants have reached the end of their commercial life and need replacement. This is known as the lock-in effect due to sunk costs and long-lived capital, which represents one of the main barriers to the diffusion of solar technologies (as well as other alternative electricity source), 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, and as we have seen happening in some EU countries, policy intervention is almost univocally recognized as the solution.

The third recognized barrier is intermittency in the supply of solar power. As a result, adequate storage systems and better grid integration are needed. Without significant developments in this complementary technology a widespread diffusion of solar power is very unlikely.

The provision of rare metals for some specific PV and CSP infrastructures represents the fourth possible limit to the diffusion of solar technologies. 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.

What emerged from the interviews is that key factors hampering the diffusion of solar technologies might also be related to their potential negative externalities. 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. Although most experts reported that industries in the PV sector are advanced in the management and recycling of toxic substances, another important concern is the use of toxic components (i.e., CdTe toxicity).[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 would instead 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, requirements with respect to water 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.

Experts were asked to reason on how non-technical barriers to market diffusion would influence the penetration of solar technologies in different markets. Under the assumption that in 2030 solar technologies would be cost-competitive with conventional fossil fuels (e.g. assuming a climate policy imposing a price on carbon), experts provided their estimates on the likelihood of alternative penetrations scenarios. In particular, experts assessed the likelihood of three scenarios, with solar power representing respectively 5%, 20% or 30% of the electricity generation mix in 2050. The experts considered three regions: OECD, fast-growing countries and developing countries. Data are shown in Figure 18.

The share of total electricity produced using solar technologies by 2050, even according to the most optimistic experts, will not be greater than 30%. When assessing the likelihood of the three penetration scenarios in OECD countries, experts show very little consensus. Conversely, the majority of experts agree in associating the highest likelihood to the 20% scenario for fast-growing countries. In addition, half of the experts associates the highest probability to the 30% penetration scenario when considering developing countries.

The argument supporting higher penetration rates in developing countries than in fast-growing countries is mainly based on the idea that solar technologies would not have to overcome problems of substituting 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 (i.e. in Africa). Ten experts specified a ceiling to the diffusion of solar technologies beyond 2050 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 nonetheless require significant investments to further improve electricity storage, the management of

[18] For abbreviations, please see note to Figure 3.

variable power and the compensation of intermittency, as well as resource and land availability.

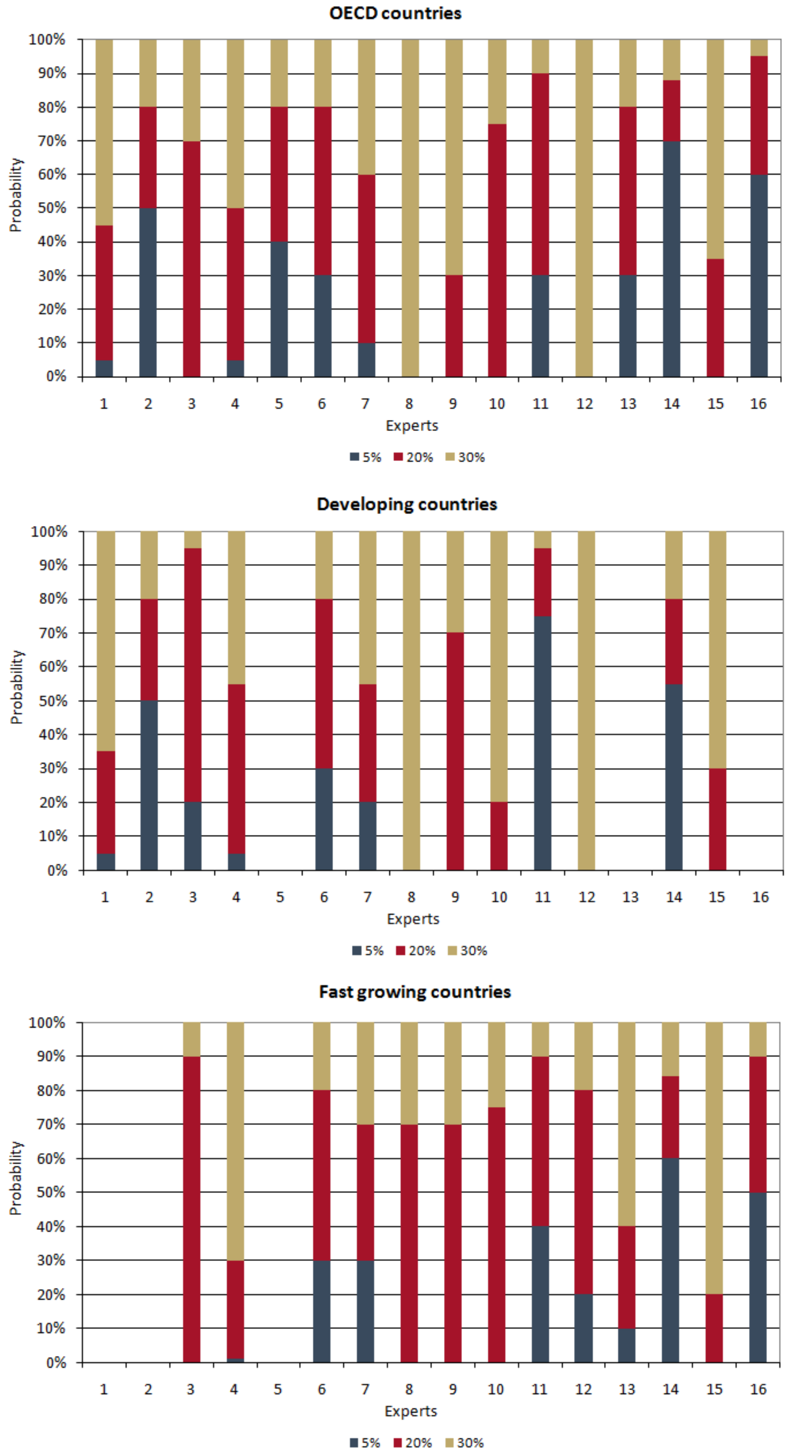

Figure 18: Percentage of solar technologies in power generation mix in 2030

Figure indicates the likelihood that each expert associates with the three penetrations rates (5%, 20% and 30%) of solar power in total power generation mix. Top panel is for OECD countries, middle panel for fast-growing countries and bottom panel for developing countries.

According to the experts surveyed in this study, even the most optimistic scenarios of solar energy diffusion into the global electricity market would be technically feasible, though they implicitly imply a quantum leap in energy storage and grid management which would be costly. Generally, the conclusions reached by the experts are in line with the projections shown in the IPCC SRREN report (IPCC, 2011). These are based on a set of scenarios reviewed under the IPCC Fourth Assessment Report[19] and describe a very wide range of possible trends in terms of potential contribution of solar energy in the global electricity supply.

7. Conclusions

Solar PV and CSP technologies represent a concrete and promising solution to reduce the dependence from fossil sources, and therefore to meet climate change policy targets while ensuring reliable energy supply. This is true both for developed and developing countries. Significant progress has been made in the last 40 years with respect to research and technical improvements. However, some technical barriers and market dynamics still hinder the commercial success of these technological options.

Assessing the potential to overcome these barriers, the RD&D effort necessary to promote this process as well as the future of solar electricity costs are key steps to support policy makers in drafting appropriate efficient energy policies. The ICARUS expert elicitation survey uses a robust elicitation protocol that results in novel evidence on the current status and future developments of both PV and CSP technologies. Its results and policy implications are of great relevance for the current debate on renewable energy technologies in Europe, as well as worldwide.

The first clear message emerging from the elicitation process is that at least one of the solar technological options analysed has a high potential to overcome technical bottlenecks in the next 20 years. This would result in lower costs of electricity production. 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. Given this evidence, the EU and its Member States should plan a long term commitment to secure stable RD&D funding to solar technologies. This conclusion clearly emerges from all the experts we interviewed.

Experts also indicate that it is necessary to develop a diversified portfolio of public RD&D funding in solar technologies. Funds should be allocated both to PV and CSP technologies and, within these, support should be secured for both more mature technologies (such as Crystalline-silicon and Thin-film PV) and more innovative ones (such as Organic PV and Third Generation PV). Clearly, the size of suggested funding is different, with more mature technologies receiving the majority of funds, while only a minor amount allocated to less mature ones, although little consensus is reached, across experts, on how to allocate the RD&D funding. This suggests that rather than “picking a winner” policy-makers should let technological options compete, although ensuring they all keep on existing.

[19] The baseline set of scenarios considers CO_2 concentrations above 600 ppm and no climate policy, while the other two set of scenarios consider CO_2 stabilization targets from 440 to 600 ppm-CO_2, and from 300 to 440 ppm-CO_2.

One important insight gained during the interviews with the experts is that the full process of RD&D should be appropriately funded. In contrast with the historical institutional choice of the EU and its Member States, the experts call for supporting demonstration activities as a core part of research in solar technologies. This will increase the likelihood that almost fully developed technologies make it through the "valley of death" and become commercially viable.

Conditional on the current level of annual RD&D investments being constant until 2030, most experts' best guesses lay within the 7.5-14.5 cUSD/kWh range. The average expected cost resulting from the expert estimates for PV technologies is 10.8 cUSD/kWh,[20] while the average expected cost for CSP technologies is 10.1 cUSD/kWh. Increasing RD&D funding by 50% lowers expected costs by roughly 20% (9.3 cUSD/kWh[21] for PV and 8.9 cUSD/kWh for CSP). Increasing public funding for solar technologies results in lower divergence of experts' estimates.

If the current RD&D expenditures are constant through 2030, the average expected cost estimate is above the highest threshold of 11.27 cUSD/kWh, which corresponds to the price of producing electricity from fossil fuel inputs in a carbon policy scenario. In this case, the probability of reaching a breakthrough is around 66%. A 50% increase in the RD&D funding leads to a significant increase in the probability of abating the costs below the 11.27 cUSD/kWh threshold by 2030: the average probability of breakthrough increases from 66% to 78%. Under the +100% scenario basically all experts agree that the cost of solar electricity would be lower than 11.27 cUSD/kWh, with a probability of breakthrough higher than 90%.

All experts agree that under the current RD&D scenario reaching either the 5.55 cUSD/kWh or the 3 cUSD/kWh target is very unlikely (<10% probability). The picture doesn't change substantially when RD&D investment increases by either 50% or 100%. According to most experts, increasing the RD&D budget by 50% (100%, respectively) would increase from 5% to 12% (21%) the average probability of reaching 5.55 cUSD/kWh.

The majority of the experts are pessimistic with respect to the possibility of reaching lower ideal cost thresholds, hence on the possibility of solar technologies becoming cost-competitive with fossil fuel technologies without any climate policy in place. The estimated probability of crossing the 5.55 cUSD/kWh threshold in 2030 is consistently below 10% across experts, and just modestly increased (but still always below 30%) as a result of doubling RD&D investments. All experts generally agree that it is unlikely that by 2030 solar electricity could be produced at costs as low as 3 cUSD/kWh.

Solar technologies, while being viable options for the future, are and will, most likely, remain intrinsically more expensive than fossil fuels, if the environmental externalities associated with the use of hydrocarbons are not 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.

[20] Excluding Concentrating PV
[21] Leaving out expert 2 does not significantly change the average expected cost figure: under the +50% RD&D scenario divergence across experts is extremely reduced.

A clear message emerging from the interviews is the evident efforts undertaken in Europe with respect to solar technology development and the high chances that the first country to reach a breakthrough in production costs will be European. However, experts recognize that also other countries (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 technical maturity and cost competitiveness are key for the success of solar power, but that non-technical issues and barriers could slow down their worldwide diffusion and consequently their success. The main obstacles to market diffusion and large-scale deployment relate to the inertia of existing power plants and to unfavourable power pricing rules. Those barriers need to be faced mainly through ad hoc policy interventions, as feed-in tariffs and standards.

The share of total electricity produced using solar technologies by 2050, even according to the most optimistic experts, will not be greater than 30%. When assessing the likelihood that solar power will represent 5%, 20% and 30% of electricity production in OECD countries, experts show very little consensus. Conversely, with respect to fast-developing countries the majority of experts associates the highest likelihood to the 20% scenario. When considering developing countries, half of the experts assign the highest probability to the 30% penetration scenario. The rationale behind this view is that in developing countries lock-in effects will be milder.

The key findings from the ICARUS expert elicitation survey on solar technologies presented in this report should be of great relevance to guide policy making and to complement information derived from climate economy models. In particular, this report can guide policy-makers and researchers alike in drafting and implementing policies in support of solar technologies. To achieve widespread deployment of this carbon free energy sources, it will be necessary to address all the challenges highlighted by the experts, from cost-reduction to non-technical barriers.

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Annex I: Elicitation protocol

Self-evaluation of expertise

Please indicate how you would evaluate your level of expertise with respect to each of the following solar technologies:

	Not familiar	Basic knowledge	Good knowledge	Expert knowledge	Among top experts
Crystalline-Si					
c-Si (Wafer-based crystalline silicon)					
c-Si ribbon or sheet					
mc-Si (Wafer-based crystalline silicon)					
mc-Si ribbon or sheet					
Thin-film PV					
a-Si (amorphous silicon)					
CdTe (cadmium telluride)					
CIS or CIGS (copper indium (gallium) diselenide)					
nano-crystalline silicon					
micro-crystalline silicon					
Concentrating PV					
c-Si up to 100x					
c-Si up to 100-1000x					
multijunction up to 100-1000x					
Organic PV					
molecular					
polymeric					
dye-sensitized solar cell					
Third generation PV					
quantum dot					
thermophotovoltaics					
hot carrier cells					
intermediate band solar cell					
up/down converters					
Concentrated Solar Power					
Parabolic troughs					
Solar power towers					
Linear Fresnel reflectors					
Dish/Stirling system					

Questionnaire

We are interested in understanding what specific conditions will lead to the commercial success of solar technologies for electricity production in the future and their diffusion thereafter. We will assume that solar technologies achieve "commercial success" when solar electricity is economically competitive with conventional fossil fuel electricity (with or without a price on carbon).

Evaluation of the status of the technology and barriers to commercial success

In this section we are interested in understanding which elements of solar technology represent **potential barriers to the commercial success of solar technologies** and how **RD&D** might help in **overcoming these barriers**. Figure A- 1 shows a simplified representation of the innovation chain which indicates the stages of the innovation, adoption and the diffusion process.

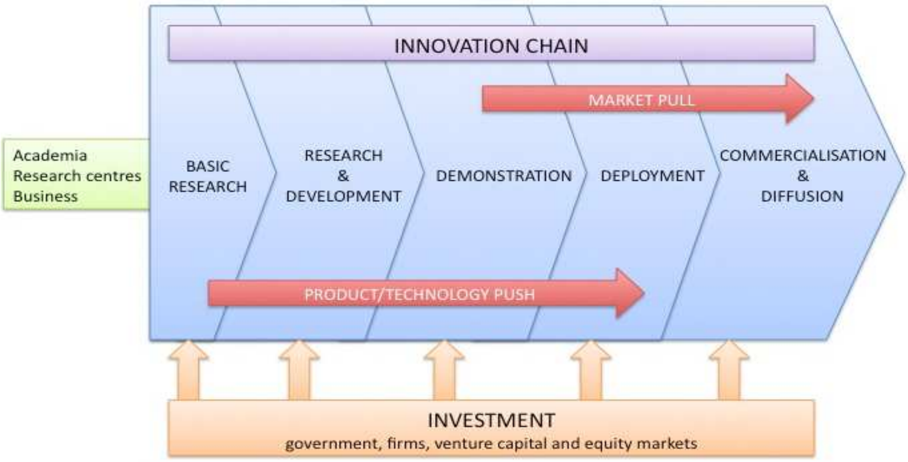


Figure A- 1: Simplified representation of the innovation chain (feedbacks are not represented). Source: IEA (2008).

In order to **evaluate the necessity of substantial advancements** to achieve commercial success, please insert a number from 1 to 3 for each technology.

1 = Current status is excellent

2 = Development can go on, but advances would be needed

3 = Substantial advances are necessary

Then, where necessary and according to your expertise, identify the main barriers and specify which stage of the RD&D process is most needed to be improved considering the following categories:

BASIC RD&D:

- for PV technologies, we include specific process improvements in: new materials development; understanding materials properties; materials optimization; …
- for CSP, we include specific process improvements in: low-cost thermal storage; low cost mirrors; selecting mirror deposition; materials' development for the heat-transfer fluid; ...

ENGINEERING AND APPLIED RD&D:

- for PV technologies, we include specific process improvements in: increasing device efficiency and reliability maintaining low costs; deposition methods; materials utilization; creating flexible modules (e.g., building incorporated materials) with a robust encapsulation material (transparent, durable, moisture proof, affordable); low-cost and reliable tracking system for concentrating PV; …
- for CSP, we include specific process improvements: air cooling and wet/dry hybrid cooling systems; increasing the efficiency and durability of specific technology components (receivers, concentrators, reflectors, and the balance of solar field), optimizing

manufacturing techniques, and reducing O&M costs by simplifying systems and learning from experience …

DEMONSTRATION:

- We include the building of pilot projects for production of electricity both with PV and with CSP technologies.

	Evaluation	Specific barriers	Type of RD&D
	1 = Current status excellent 2 = Advances needed 3 = Substantial advances needed		A= Basic RD&D B= Applied RD&D C = Demonstration
Technology			
Crystalline-Si			
Thin-film PV			
Concentrating PV			
Organic PV			
Third generation PV			
CSP			

Please, indicate which of the identified barriers could not be overcome with an increase in the level of investment in RD&D: …………………………………………………

Evaluation of RD&D budget allocation

We are interested in assessing how the **RD&D budget should be allocated** over the period 2010-2030 to make solar technologies commercially successful in 2030. We are aware that the RD&D allocation would change over time. However, for simplicity, we will assume that the chosen allocation will be replicated every year until 2030. Please factor this into your estimates.

Consider the current annual budget and assuming that it corresponds to **100 chips**, please allocate these chips among the selected research areas by writing the number of chips in each cell:

0 chips = there is no need for RD&D spending in this area for the given technology (e.g. technology is already mature; further advances are not foreseeable; …)

> 0 chips = with RD&D spending in this area the technology is more likely to be commercially successful in 2030.

Technology	Number of chips
Crystalline-Si	
Thin-film PV	
Concentrating PV	
Organic PV	
Third generation PV	
Concentrating Solar Power	

Evolution of solar technologies cost in different RD&D funding scenarios

We are interested in analysing the **evolution of the expected cost of electricity produced with solar technologies** under different RD&D funding scenarios. The aim is then to assess whether solar generated electricity will eventually become competitive with fossil fuel generated electricity (with or without accounting for a carbon tax). Cost competitiveness does not necessarily imply immediate and extensive diffusion of solar technologies, as there might exist other barriers to diffusion that we will investigate in the subsequent section. For now, let us concentrate on cost improvements.

Estimates of the costs of electricity produced using solar technologies (please refer to Figure 3 and to Table 1 for current estimates of PV module costs and of CSP technologies, respectively) crucially depend on (assumptions about) the following factors:

Technology Efficiency (defined as the fraction of incident solar energy converted into DC electrical energy)

Lifetime (defined as the number of years of operation)

Module Areal Cost ($\$/m^2$)

Balance of system (BOS) **cost** ($\$/m^2$) (defined as the costs of all non-photoactive parts)

Peak insolation power (the peak amount of solar energy received on PV cells)

Discount rate

The current status of the above characteristics could be improved via further RD&D in order to lower the costs of solar electricity production. To understand how technical characteristics influence costs, please refer to the formulae in the appendix A.

While answering the questions on solar electricity costs, please consider <u>no incentive or subsidy</u>.

If you already have in mind a specific amount of annual RD&D investment (for the next 20 years) and/or a time horizon that would allow solar technologies to achieve commercial success, please state it now.

………..……………………………………………………………………………

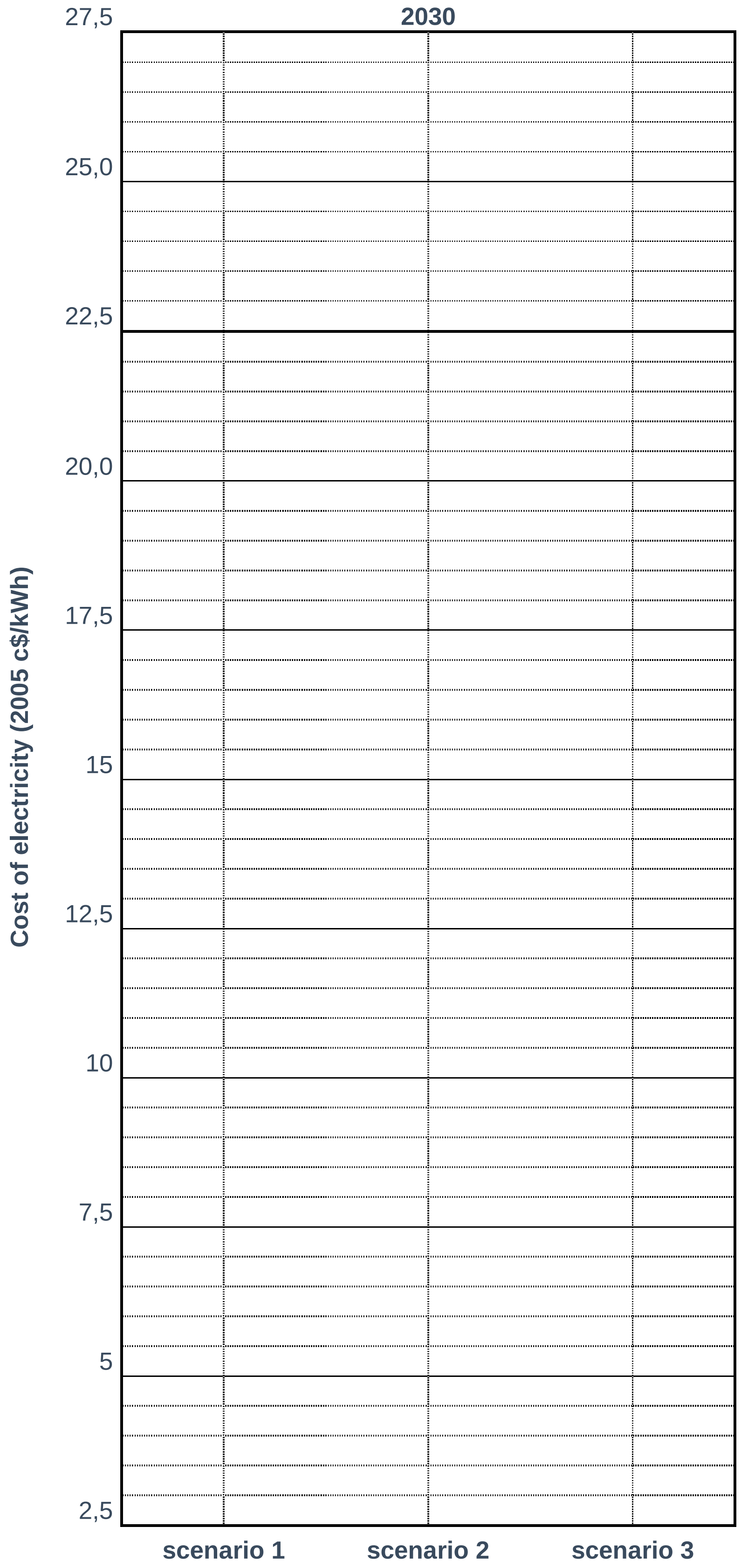
A) Please, estimate the expected cost of electricity produced with solar technologies in 2030 under the following public RD&D investment scenario (you might refer to one or more solar technologies).

> ***Scenario 1****: Suppose that* ***research in the field of Solar technologies receives the current yearly amount of R&D expenditures for each year until 2030.*** *Please provide your estimates of the expected* ***cost of electricity*** *under this funding scenario. (if needed, please refer to Figure 5 reporting the RD&D investment in solar). Please, draw the segment of expected module costs in the graph provided in the following page.*

(Other RD&D scenarios will be proposed to you during the interview, contingent on your response.)

To minimize the overconfidence bias, we remind you to reason in the following way:

1. Use a pencil and eraser, rather than pen, so that you may revise your answers as necessary.
2. Think of the highest possible value and the lowest possible value. This is your total estimate range.
3. For each technology, provide the 90th percentile estimate of the characteristics in question.
4. Ask yourself if there are any circumstances that would result in a value higher or lower than the value that you have reported. If so, please revise your estimate.
5. For each technology, provide the 10th percentile estimate of the characteristics in question.
6. Ask yourself if there are any circumstances that would result in a value higher or lower than the value that you have reported. If so, please revise your estimate.
7. Having set your 10th and 90th percentile estimates, please provide your 50th percentile estimate, or best estimate.


2030
Cost of electricity (2005 c$/kWh)
27,5
25,0
22,5
20,0
17,5
15
12,5
10
7,5
5
2,5
scenario 1
scenario 2
scenario 3

B) Please, estimate the probability that the cost of electricity produced with solar technologies in 2030 under the following public RD&D investment scenarios will be lower than the cost of electricity from fossil fuels (with and without a price on carbon) and the cost of electricity from nuclear.

Scenario 1*: Suppose that* ***research in the field of Solar technologies receives the current yearly amount of R&D expenditures for each year until 2030.*** *Please complete the table below.*

(Other RD&D scenarios will be proposed to you during the interview, contingent on your response.)

	Probability			
Cost of solar electricity	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
≤ 11.27 c$/kWh				
≤ 5.55 c$/kWh				
≤ 3 c$/kWh				

In this section, we have asked you to discuss the cost of solar technologies. Please, indicate whether upon answering the questions you were referring to the technology that you consider to be the most promising or to a mix of technologies.

………..…………………………………………………………………………………

When providing solar electricity costs in section 3, were you referring to an EU country?

□ yes

□ no

Upon answering the question did you have in mind an optimal allocation of RD&D effort as you specified using ‘chips’ in section 3 or the current allocation as provided in figure 5?

………..…………………………………………………………………………………

Discussion questions on knowledge spillovers and externalities

Which of the following countries do you think is more likely to be the first to reach a commercially successful breakthrough in solar technologies?

- □ Europe
- □ USA
- □ Japan
- □ China
- □ Other (specify) ……………………………

Do you think that the INNOVATION resulting from the EU R&D program will be affected by other countries' R&D programs and innovation (KNOWLEDGE SPILLOVERS)?

□ SECRECY/NO COOPERATION – NO KNOWLEDGE SPILLOVERS

□ COOPERATION – KNOWLEDGE SPILLOVERS – NEED FOR OWN RD&D TO DEVELOP ABSORPTIVE CAPACITY

□ NO SECRECY – FULL KNOWLEDGE SPILLOVERS – LITTLE ROLE FOR OWN RD&D PROGRAM

Are you concerned about negative externalities which might derive from the diffusion of solar technologies and might impact the environment and society as a whole?

……………………………………………………………………………………….

Diffusion

In this last section, we are interested in assessing the conditions that would set back or even prevent the diffusion of solar technologies, even assuming they have become competitive with fossil fuelled power generation.

We have selected a number of factors which could represent the non-technical barriers to the diffusion of solar technologies. Please confirm whether the proposed barriers are important and if necessary please add any further factors of constraint.

Using the table below, assess the importance of each of the following factors limiting the diffusion of solar technologies, by providing a number from **1 (low)** to **3 (high)**.

Please also select from the following list the potential solutions to overcome the barriers that you consider as the most important with respect to each barrier, and if necessary add specific comments. The suggested solutions include:

- policy interventions,
- additional investments,
- education,
- marketing.

Potential barriers	Importance of the barrier 1 low 2 medium 3 high	Possible solutions and comments PI policy interventions, AI additional investments, ED education, MK marketing.
Long-lived capital stock and turnover of power plants		
Intermittency		
Geographical constraints		
Unfavourable power pricing rules		
Rare metals supply		
Land availability		
…………………………………		

In this next section, assume that in 2030 solar technologies will be technically ready to compete with conventional fossil fuels. Considering the non-technical barriers that you have previously identified, we now ask you to provide your estimate on the **diffusion trend of the solar technologies in power generation**.

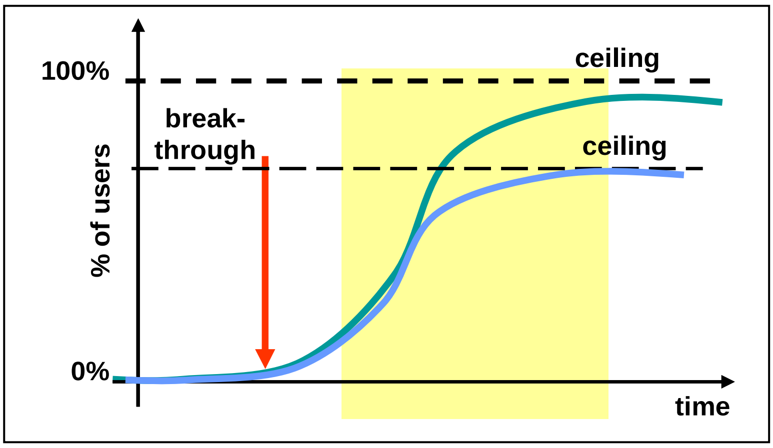


Figure A- 2: S-curve of technology adoption

Since the date of invention, technologies can experience slow adoption or fast adoption. Figure A- 2 portrays a typical s-curve describing technology adoption. If adoption is slow, many years elapse between the date of first market appearance and the adoption of technology by the majority of firms. Figure A- 3 provides a concrete example by showing the penetration of nuclear electric power in the US electricity sector over the last 60 years.

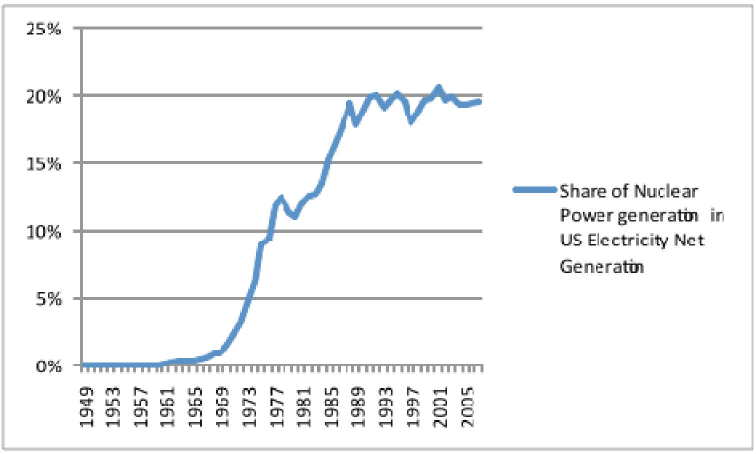


Figure A- 3: Share of Nuclear Electric power in US Electricity Net Generation, 1949- 2007

Source: http://www.eia.doe.gov/emeu/aer/txt/ptb0802a.html

We propose three scenarios, which correspond to specific penetration rates of solar technologies within the power generation mix. With the aim to facilitate the understanding of the proposed scenarios, keep in mind that currently 30% of power generation in Western Europe is provided by nuclear and 20% by natural gas.

Please, assign a probability to the following scenarios:

	Percent of power generation by 2050			
	5%	20%	30%	
OECD				= 100%

Fast growing				= 100%
Developing countries				= 100%

We would like these three scenarios to loosely represent all possible options, so we ask you to ensure that the sum of probabilities is 100%.

The diffusion trend of solar technologies will eventually reach a *ceiling*. Can you specify what this ceiling may be (as percent of total power generation)?

…………………………………………………………………………………………

What do you believe will be the major causes of the ceiling?

…………………………………………………………………………………………

Once the technology reaches the market in the first country, how long will it take for the technology to be diffused to other OECD countries?

- □ no time lag
- □ 5 years
- □ 10 years
- □ more (specify) …………

Once the technology reaches the market in the first country, how long will it take for the technology to be diffused to fast growing countries?

- □ no time lag
- □ 5 years
- □ 10 years
- □ more (specify) …………

Once the technology reaches the market in the first country, how long will it take for the technology to be diffused to other non OECD countries?

- □ no time lag
- □ 5 years
- □ 10 years
- □ more (specify) …………

Annex II: Cost of electricity produced with solar technologies

The cost of PV electricity can be estimated using the following equation (DOE, 2005) which depends on key parameters such as solar cell conversion efficiency and real cost of the module:

$$C = \frac{Module\, area\, \cos t + BOS}{efficiency \cdot 1000} + Cost\, Power\, Conditioning$$

where:

C is the cost per Watt of incident solar irradiance at peak solar intensity, \$/Wp;

Module areal cost is the cost of modules only per unit area, $\$/m^2$;

efficiency is the fractional conversion efficiency, %;

1,000 W/m² is the assumed peak insolation power (namely the peak amount of solar energy received on PV cells of 1000 W per square meter);

BOS areal cost is the balance of systems (support structure, installation, wiring, land, etc.) cost per unit area, $\$/m^2$;

cost of power conditioning, AC-DC inverter, is assumed equal to 0.10 \$/Wp.

The following equation converts the PV system cost per peak watt (\$/Wp) in the cost of the produced electricity (\$/kWh):

$$PV\ \cos t\ of\ electricity = \frac{C \cdot FCR \cdot 1000}{E}$$

The cost of electricity produced from PV (c\$/kWh) is calculated dividing the cost of the PV system *C* (\$/Wp) by the amount of electricity produced in one year (*E*, measured in Wh). The term *FCR* indicates the fixed charge rate, assuming a lifetime of *N* years and a discount rate (r) of 10%:

$$FCR = \sum_{t=1}^{N} \frac{1}{(1+r)^t}$$

The amount of electricity produced in one year (*E*, Wh) is derived assuming that the PV system operates at 20% of peak power on average (*f*) over the year (8760 hours per year). The PV peak power (*P*) is derived from the peak insolation power of 1000 W/m^2, divided by the PV cell efficiency.

$$E = P \cdot f \cdot 8760$$

For some of the PV technologies considered in this questionnaire, we provide in Table A- 1 an example of the values of the different parameters and the deriving final cost of electricity applying the formulae above. Improvements of the technological parameters would result in a reduction of the expected costs.

Table A- 1 Current and expected costs of electricity produced from PV, according to different values of technological endpoints. Source: (a) Baker et al., 2009

Technology	Efficiency	Lifetime (yr)	Module areal cost (2005$/m^2)	Cost of PV module (2005$/m^2)	BOS (2005$/m^2)	**Cost (2005 c$/kWh)**
Current						
c-Si - Wafer-based crystalline silicon (a)	10%	30	350	3,50	250	**32,82**
a-Si - amorphous silicon	8%	20	-	1,50	250	**25,42**
Expected						
Purely organic PV (pessimistic) (a)	15%	30	50	-	75	**5,02**
Purely organic PV (optimistic) (a)	31%	15	50	-	75	**2,18**
Thin film (a)	15%	30	50	-	75	**5,02**
Third generation (quantum dots and multi-junction cells) (a)	36%	30	100	-		**3,15**

The cost of electricity from CSP ($/kWh) can be estimated by using the following equation (Enermodal, 1999):

$$CSP\ \text{cost of electricity} = \frac{I \cdot FCR + C_{o\&m}}{E}$$

where *I* ($) is the installed capital cost, *Co&m* are the annual operation and maintenance costs, *E* is the annual energy production (MWh/yr), and *FCR* indicates the fixed charge rate, assuming a lifetime of *N* years and a discount rate (*r*) of 10%:

$$FCR = \sum_{t=1}^{N} \frac{1}{(1+r)^t}$$

The installed capital cost (*I*, $) can be assessed by multiplying the investment cost per MW (I_{spec}, $/kW) and the total plant power (*P*, MW):

$$I = I_{spec} \cdot P \cdot 1000$$

The operation and maintenance costs ($C_{o\&m}$, $/yr) are a percentage of the installed capital cost ($f_{o\&m}$), assumed at 2%:

$$C_{o\&m} = f_{o\&m} \cdot I$$

The annual energy production (*E*, MWh/yr), is estimated by multiplying the total plant power (*P*, MW), the plant capacity factor (*f*) and the hours per year (8760 hours per year):

$$E = P \cdot f \cdot 8760$$

For some of the CSP technologies considered in this questionnaire, we provide in Table A- 2 an example of the values of the different parameters and the deriving final cost of electricity applying the formulae above. Improvements of the technological parameters would result in a reduction of the expected costs.

Table A- 2 Current and expected costs of electricity produced from CSP.

	Investment per kW	O&M factor	Total plant power	Plant capacity factor	Annual energy production	**Electricity cost**
	2005$/kW		MW		MWh/yr	**2005c$/kWh**
Current						
Parabolic trough (a)	5074	2%	50	0,30	131.400	**22,06**
Power tower (b)	3878	2%	10	0,27	23.652	**18,74**
Expected near term						
Parabolic trough (c)	3490	2%	100	0,33	289.080	**13,80**
Expected advanced						
Parabolic trough (c)	2809	2%	200	0,53	928.560	**6,91**
(a) SER, 2010; (b) Solúcar, 2006; Romero et al., 2002; (c) Price et al., 2002						

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