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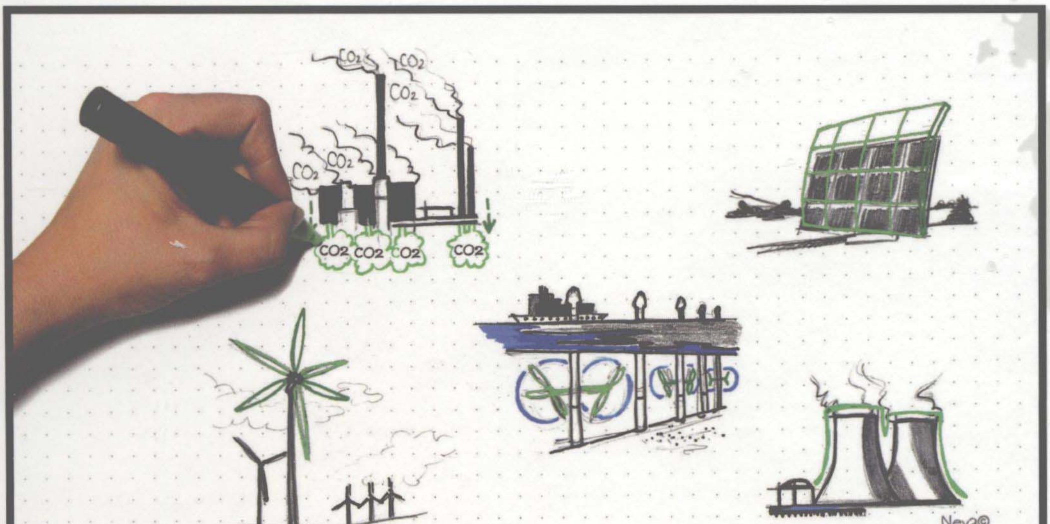
The Future of Carbon-free Energy Technologies



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THE FONDAZIONE ENI ENRICO MATTEI (FEEM) SERIES ON ECONOMICS, THE ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

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Innovation under Uncertainty
The Future of Carbon-free Energy Technologies
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ICARUS Outputs

The outputs of the ICARUS project are already published in:

Anadon, L.D., V. Bosetti, M. Bunn, M. Catenacci and A. Lee (2012), 'Expert judgments about RD&D and the future of nuclear energy', *Environmental Science and Technology*, **41**(21), 11497–504, DOI: 10.1021/es300612c.

Bosetti, V., M. Catenacci, G. Fiorese and E. Verdolini (2012), 'The future prospect of PV and CSP solar technologies: An expert elicitation survey', *Energy Policy*, **49**, 308–317.

Catenacci, M., G. Fiorese, E. Verdolini and V. Bosetti (2013), 'Going electric: Expert survey on the future of battery technologies for electric vehicles', *Energy Policy*, **61**, 403–413.

Fiorese, G., M. Catenacci, V. Bosetti and E. Verdolini (2014), 'The power of biomass: experts disclose the potential for success of bioenergy technologies', *Energy Policy*, **65**, 94–114.

Fiorese, G., M. Catenacci, E. Verdolini and V. Bosetti (2013), 'Advanced biofuels: Future perspectives from an expert elicitation survey', *Energy Policy*, **56**, 293–311.

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Introduction

Valentina Bosetti, Michela Catenacci, Giulia Fiorese, Elena Verdolini and Laura Aleluia

Much has been said on how to reduce current anthropogenic emissions with the portfolio of existing low-carbon and carbon-free technologies (see, for example, Arzivu et al., 2011). However, stabilization of atmospheric concentrations of greenhouse gases to a safe level can only be achieved if, eventually, net emissions fall to zero.

There is only one way to achieve this goal: through some kind of technological revolution, which necessarily requires high spending on research, development and demonstration (RD&D). Innovation in the energy sector should be aimed both at reaching a more efficient use of energy and at diffusing carbon-free technologies on a large scale. The resulting development and deployment of more efficient generation technologies is not only going to meet the growing concern for global warming, but also the more general ambition for sustainable development.

Although RD&D is admittedly only one of the determinants of future energy technology costs, assessing the RD&D effort necessary to promote cost improvements and to overcome non-technical diffusion barriers is a key step to draft appropriate efficient energy policies. The study of the evolution of clean energy technologies is particularly relevant for European countries, in light of their leading position in climate negotiations (EC, 2009a,b) and the crucial role of innovation these countries have been aiming at through the Lisbon Agenda (EC, 2005).

The process of innovation is, however, characterized by uncertainty, hence cost assessments will need to take into careful account and report these uncertainties. A large body of literature tries to capture the main drivers of the innovation process by looking at past data. However, when specific technologies are concerned, there might be non-reproducible events that make it hard to assess the effectiveness of a specific RD&D program simply looking at the past. To overcome this, structured expert judgments have been extensively used to assess the probabilistic effect of RD&D on the future cost of technologies.

This volume collects the results of a four-year European Research Council funded project which focused on innovation and uncertainty in carbon-free energy technologies (ICARUS project, www.icarus-project.org). The ICARUS project studies innovation in the energy sector using a combination of research approaches, ranging from econometric analysis to modelling and expert elicitations. In particular, we present here the insights from a set of expert elicitation surveys aiming at assessing probabilistic information on the impact of public European RD&D investment on the future cost of different low-carbon energy technologies. More than 120 energy technology experts (see Table 1) have been interviewed using structured elicitation protocols to collect a wide range of information, from expected energy costs to more detailed information such as technological barriers.

Focus of the expert elicitations were selected key energy technologies, which are expected to play a crucial role in reducing GHGs emissions. They can be classified as either carbon-free energy technologies for the production of electricity (solar photovoltaic and concentrated solar power; biomass for the production of electricity; nuclear power) or carbon-free solutions for transportation (biofuels for transportation; batteries for electric drive vehicles).

In Chapter 1 we present the elicitation protocol, which was structured based on the main literature on decision analysis, to guide the expert elicitation processes and minimize the occurrence of biases and errors in the experts' estimates. The same methodology was applied to build all surveys, and was based on the submission of structured questionnaires during face-to-face interviews. Within each survey, the experts were asked to: (i) evaluate the level of maturity of each technology option; (ii) allocate the RD&D budget among the different technology options, with the aim to support technical development and deployment; (iii) assess the effect of an increase in public EU RD&D investments on the cost of each technology in 2030; (iv) address the technology transfer dynamics, externalities and market barriers which could affect the widespread diffusion of each technology. A notable exception is the survey on nuclear power, which was carried out with EU experts in parallel with a US-based project developed at the Energy Technology Innovation Policy research group, Harvard University. In this case, a two-step approach was followed and experts were first asked to compile individual web questionnaires to which a workshop followed.

Chapter 2 presents results for solar photovoltaic and concentrated solar power technologies, while Chapter 3 focuses on biomass power production and Chapter 4 on nuclear power technologies. Chapter 5 illustrates the outputs of the surveys on biofuels technologies for transportation and Chapter 6 presents the analysis carried out on batteries for fully electric and hybrid vehicles.

In the rest of this introductory chapter we want to summarize some key findings across technologies through few overview graphs. Due to the comparability of data collection effort, we will focus on a comparison of

Table 1 Experts participating the ICARUS project surveys

Name	Affiliation	Country
(a) Solar		
Rob Bland	McKinsey	USA
Luisa F. Cabeza	University of Lleida	Spain
Roberta Campesato	Centro Elettrotecnico Sperimentale Italiano	Italy
Carlos del Canizo Nadal	Universidad Politecnica de Madrid	Spain
Aldo Di Carlo	UniRoma2	Italy
Ferrazza Francesca	Ente Nazionale Idrocarburi	Italy
Paolo Frankl	International Energy Agency	UK
Arnulf Jäger-Waldau	European Commission DG JRC	Germany
Roland Langfeld	Schott AG.	Germany
Ole Langniss	FICHTNER GmbH & Co. KG	Germany
Antonio Luque	Universidad Politecnica de Madrid	Spain
Paolo Martini	Archimede Solar Energy	Italy
Christoph Richter	German Aerospace Center	Germany
Wim Sinke	Energy Research Centre	Netherlands
Rolf Wüstenhagen	University of St. Gallen	Switzerland
Paul Wyers	Energy Research Centre	Netherlands
(b) Bioenergy		
Alessandro Agostini	JRC – Joint Research Centre	Netherlands
Göran Berndes	Chalmers University of Technology	Sweden
Rolf Björheden	Skogforsk – the Forestry Research Institute of Sweden	Sweden
Stefano Capaccioli	ETA – Florence Renewable Energies	Italy
Ylenia Curci	Global Bioenergy Partnership	Italy
Bernhard Drosg	BOKU – University of Natural Resources and Life Science	Austria
Berit Erlach	TU Berlin – Technische Universität Berlin	Germany
André P.C. Faaij	Utrecht University	Netherlands
Mario Gaia	Turboden s.r.l.	Italy
Rainer Janssen	WIP – Renewable Energies	Germany
Jaap Koppejan	Procede Biomass BV	Netherlands
Esa Kurkela	VTT – Technical Research Centre of Finland	Finland
Sylvain Leduc	IIASA – International Institute for Applied Systems Analysis	Austria
Guido Magneschi	DNV KEMA	Netherlands
Stephen McPhail	ENEA – Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	Italy
Fabio Monforti-Ferrario	JRC – Joint Research Centre	Italy

(continued overleaf)

Table 1 Experts participating the ICARUS project surveys (continued)

Name	Affiliation	Country
(c) Nuclear		
Markku Anttila	VTT (Technical Research Centre of Finland)	Finland
Fosco Bianchi	Italian National Agency for New Technologies, Energy & Sustainable Economic Development (ENEA)	Italy
Luigi Bruzzi	University of Bologna	Italy
Franco Casali	ENEA; IAEA; University of Bologna	Italy
Jean-Marc Cavedon	Paul Scherrer Institut	Switzerland
Didier De Bruyn	SCK CEN, the Belgian Nuclear Research Centre	Belgium
Marc Deffrennes	European Commission, DG TREN, Euratom	Belgium
Allan Duncan	Euratom, UK Atomic Energy Authority, HM Inspectorate of Pollution	UK
Dominique Finon	Centre National de la Recherche Scientifique (CNRS), Centre International de Recherche sur l'Environnement et le Developpement	France
Konstantin Foskolos	Paul Scherrer Institut	Switzerland
Michael Fuetterer	Joint Research Centre – European Commission	Netherlands
Kevin Hesketh	UK National Nuclear Laboratory	UK
Christian Kirchsteiger	European Commission, DG Energy and Transport	Netherlands
Peter Liska	Nuclear Power Plants Research Institute	Slovak Republic
Bruno Merk	Institute of Safety Research Forschungszentrum Dresden-Rossendorf	Germany
Julio Martins Montalvão e Silva	Instituto Tecnologico e Nuclear	Portugal
Stefano Monti	Italian National agency for new technologies, Energy and sustainable economic development (ENEA)	Italy
William Nuttall	University of Cambridge	UK
Francois Perchet	World Nuclear University	UK
Enn Realo	Radiation Safety Department, Environmental Board, Estonia; University of Tartu	Estonia
Hans-Holger Rogner	International Atomic Energy Agency (IAEA)	Austria
David Shropshire	Joint Research Centre – European Commission	Netherlands
Simos Simopoulos	National Technical University of Athens; Greek Atomic Energy Commission, NTUA	Greece
Renzo Tavoni	Italian National agency for new technologies, Energy and sustainable economic development (ENEA)	Italy
Andrej Trkov	Institute Jozef Stefan	Slovenia
Harri Tuomisto	Fortum Nuclear Services Oy	Finland

Table 1 (continued)

Name	Affiliation	Country
Ioan Ursu	Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH)	Romania
Bob van der Zwann	Energy Research Centre of the Netherlands (ECN)	Netherlands
Georges van Goethem	European Commission, DG Research, Euratom	Belgium
Simon Webster	European Commission, DG Energy, Euratom	Belgium
John F. Ahearne	National Academy of Sciences, Sigma Xi, Nuclear Regulatory Commission	USA
Johnhong Ahn	University of California, Berkeley	USA
Edward D. Arthur	Advanced Reactor Concepts, Los Alamos National Laboratory, University of New Mexico	USA
Sydney J. Ball	Oak Ridge National Laboratory	USA
Ashok S. Bhatnagar	Tennessee Valley Authority Nuclear Operations	USA
Robert J. Budnitz	Lawrence Berkeley National Laboratory, Nuclear Regulatory Commission	USA
Douglas M. Chapin	MPR Associates	USA
Michael L. Corradini	University of Wisconsin-Madison	USA
B. John Garrick	US Nuclear Waste Technical Review Board	USA
Michael W. Golay	Massachusetts Institute of Technology	USA
Eugene S. Grecheck	Dominion Energy	USA
Pavel Hejzlar	TerraPower	USA
J. Stephen Herring	Idaho National Laboratory	USA
Thomas Isaacs	Stanford University, Lawrence Livermore National Laboratory	USA
Kazuyoshi Kataoka	Toshiba	USA
Andrew C. Klein	Oregon State University	USA
Milton Levenson	Oak Ridge National Laboratory, Bechtel, EPRI	USA
Regis Matzie	Westinghouse	USA
Andrew Orrell	Sandia National Laboratory	USA
Kenneth L. Peddicord	Texas A&M University	USA
Per F. Peterson	University of California, Berkeley	USA
Paul S. Pickard	Sandia National Laboratory	USA
Burton Richter	Stanford University, Lawrence Livermore National Laboratory	USA
Geoffrey Rothwell	Stanford University	USA
Pradip Saha	GE Hitachi Nuclear Energy	USA
Craig F. Smith	Lawrence Livermore National Laboratory, Monterey Naval Postgraduate School	USA
Finis Southworth	Areva North America	USA
Temitope Taiwo	Argonne National Laboratory	USA

(continued overleaf)

Table 1 Experts participating the ICARUS project surveys (continued)

Name	Affiliation	Country
Neil E. Todreas	Massachusetts Institute of Technology	USA
Edward Wallace	NuScale, PBMR Ltd. , Tennessee Valley Authority	USA
(d) Biofuels		
David Chiaramonti	Università degli Studi di Firenze	Italy
Jean-Francois Dallemand	Joint Research Centre (Ispra)	France
Ed De Jong	Avantium Chemicals BV	Netherlands
Herman den Uil	Energy Research Centre of the Netherlands (ECN)	Netherlands
Robert Edwards	Joint Research Centre (Ispra)	UK
Hans Hellsmark	Chalmers University of Technology	Sweden
Carole Hohwiller	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)	France
Ingvar Landalv	CHEMREC	Sweden
Marc Londo	Energy Research Centre of the Netherlands (ECN)	Netherlands
Fabio Monforti-Ferrario	Joint Research Centre (Ispra)	Italy
Giacomo Rispoli	Eni S.p.A.	Italy
Nilay Shah	Imperial College London	UK
Raphael Slade	Imperial College London	UK
Philippe Shild	European Commission	Germany
Henrik Thunman	Chalmers University of Technology	Sweden
(d) Batteries		
Michel Armand	Université de la Picardie	France
Pierpaolo Cazzola	International Energy Agency	Italy
Damien Crespel	Société Véhicules Electrique	France
Claudio Fonsati	Micro-Vett	Italy
Sergio Leonti; Vittorio Ravello	FIAT	Italy
Giuseppe Lodi	FIAMM	Italy
Adolfo Perujo y Mateos del Parque	Joint Research Centre	EU
John L. Petersen	Fefer Petersen & Cie	Switzerland
Bruno Scrosati	Università degli Studi di Roma 'La Sapienza'	Italy
Patrice Simon	Université Paul Sabatier	France
Jean Marie Tarascon	Université de la Picardie	France
Christian Thiel	Joint Research Centre	EU
Margaret Wohlgahrt-Mehrens	ZSW ULM	Germany
Karim Zaghib	Ireq	Canada

results from the solar, bioenergy, biofuel and battery surveys, leaving out the results of the nuclear survey (presented in Chapter 4).

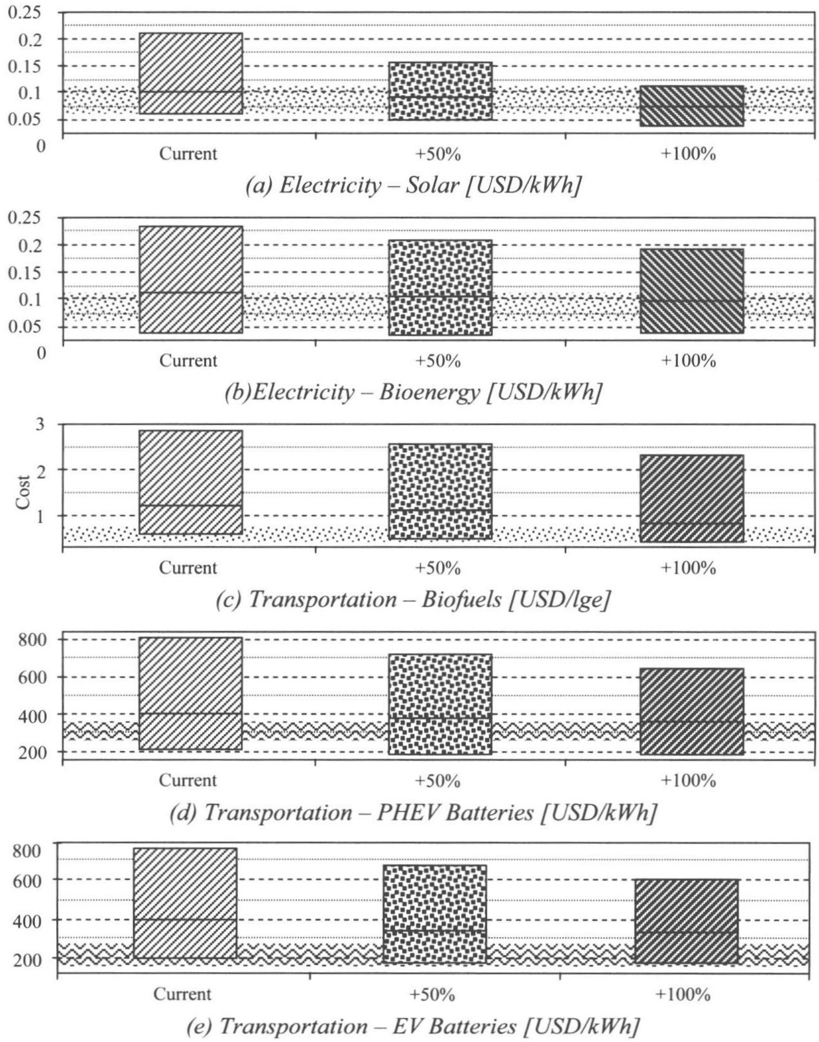
Aim of the surveys was to characterize the effect of RD&D spending on technology costs. Hence, the main purpose was to elicit the future cost of a specific technology (e.g. Wafer-based crystalline silicon PV) or of a family of technologies (e.g. solar PV) in 2030. The cost estimates (90th, 10th and 50th percentiles) were elicited conditional on given innovation effort scenarios. Specifically, three different scenarios of EU public funding for RD&D were considered, under the assumption that investments would be evenly spread over the years from today to 2030.[4] We considered a 'Current RD&D' scenario in which current annual EU public RD&D would be kept through 2030. In a second scenario, '+50% RD&D', we assumed a 50 percent increase of public EU RD&D investment sustained until 2030; finally in a third scenario, '+100% RD&D', annual public EU RD&D was assumed to scale up to twice the current levels.

Compared with the current funding priorities of the EU, all experts suggested a redistribution of investments to the whole chain of research, development, demonstration and deployment, with large emphasis on demonstration and early deployment for some key technologies. Even though experts had different areas of expertise, almost all recommended a diversified portfolio, including technologies that were not necessarily within their specific field. This suggested that, rather than 'picking a winner', experts are supporting a competitive approach ensuring that most technological options keep on existing.

On future costs, experts seemed to agree on the fact that power technologies (solar PV and bioenergy) have mild to good prospects of costs abatement, so much as to compete with fossil fuelled alternatives in the years to come, although only when a moderate carbon policy is actually in place. Conversely, transportation technologies (biofuels and batteries for electric drive vehicles) are deemed as having scarce probabilities to become competitive with traditional fossil combustion options even in the presence of a moderate price on carbon, although increasing RD&D levels could remarkably improve the situation.

Figure 1 summarizes our results in this respect by plotting, for each technology, the distribution of technology costs in 2030 aggregated over the experts under the different RD&D scenarios.

All technologies would positively react to an increase in RD&D investments, although for biofuels and batteries the experts were, in aggregate, more pessimistic on the magnitude of the effect. In general, the effect of RD&D is not only that of decreasing the aggregated best estimate of future cost (the horizontal line in Figure 1), but also that of reducing more the worst case outcome, thus affecting the 90th percentile cost level.



Notes: The boxes stretch from the 10th to the 90th percentiles, and the horizontal black lines indicates the 50th percentiles. Each row reports values for a different technology. The dotted areas in the graphs (a), (b) and (c) represent the cost range for the fossil alternative. These are projection made through an integrated assessment model, WITCH (Bosetti et al., 2006). The range is produced by assuming no climate policy (lowest level) or moderate climate policy (upper level). In the last two graphs (d) and (e) the wavy area represent instead the range of projections for the cost of batteries from the literature (Cluzel and Douglas, 2012; Kromer and Heywood, 2007).

Figure 1 Costs projections aggregated for all experts for the three RD&D scenarios

In the case of solar and bioenergy technologies, if RD&D investments were to increase by 50 percent or even by 100 percent the aggregated best estimates would most likely be in the range of their fossil fuel competitors. The story is different for transportation technologies: even under the 100 percent RD&D increase the best estimates are above their cost targets.

What is shown in Figure 1 is the result of the aggregation of data collected from different experts and it is important to keep in mind that experts had very different views, frequently far from the aggregated picture. In this way, in the following chapters, we will mostly report the individual data rather than the aggregate figures, in order to provide a complete picture of the collected information. It is then up to the policy makers or to the final users of the data to decide whether and how to aggregate this information and how to account for extremes, outlier and surprises. Below we provide a glimpse of this issue by discussing the level of consensus among experts regarding future cost estimates. Consensus varies across technologies, with level of RD&D spending and with the percentile that is considered, and it is a good indicator for the level of reliability of the aggregate figure. Let us start considering the difference in consensus among technologies and RD&D levels. Figure 2 shows the coefficient of variation[6] of the 50th percentile of experts' estimates, which one can read as the level of disagreement, for all technologies under the three RD&D scenarios. Consensus on the best estimate is highest for solar technologies, while batteries for EDV are in the middle, and lowest consensus emerges for bio-technologies. In the case of

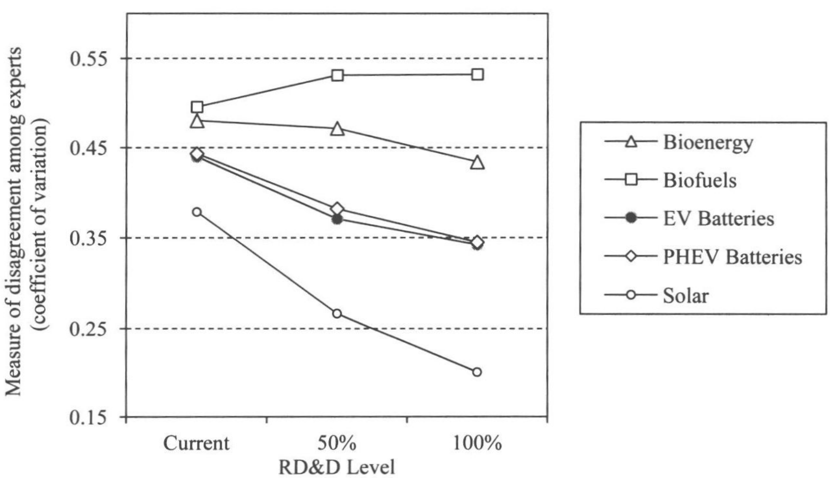


Figure 2 Coefficient of variation of experts' best estimate of 2030 cost projections (50th percentiles) for all technologies and RD&D scenarios