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Experts Disclose the
Potential for Success of
Bioenergy Technologies**

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Summary

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Keywords: Expert Elicitation, Research, Development and Demonstration, Bioenergy

JEL Classification: Q42, Q55

The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement n° 240895 – project ICARUS “Innovation for Climate Change Mitigation: a Study of energy R&D, its Uncertain Effectiveness and Spillovers”. We thank the participating experts listed in Table 3, Agostino Gambarotta (Università di Parma) and Paolo Magni (Fondazione Politecnico di Milano) who helped us for the pilot tests. We also wish to thank Erin Baker (University of Massachusetts), Jacopo Crimi and Barbara Racah for their contribution and assistance. The usual disclaimers apply.

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The power of biomass: experts disclose the potential for success of bioenergy technologies

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ABSTRACT: This paper focuses on technologies which use thermo-chemical or biochemical processes to convert biomass into electricity. We present the results from an expert elicitation exercise involving sixteen leading experts coming from different EU Member States. Aim of the elicitation was to assess the potential cost reduction of RD&D (Research, Development and Demonstration) efforts and to identify barriers to the diffusion of these technologies. The research sheds light on the future potential of bioenergy technologies both in OECD (Organisation for Economic Co-operation and Development) and non-OECD countries. The results we present are an important input both for the integrated assessment modeling community and for policy makers who draft public RD&D strategies.

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1 Introduction

Biomass is the biodegradable fraction of products, wastes or residues from agriculture, forestry, industry or households (Angelis-Dimakis et al., 2011). Biomass is a well-known and widely used renewable source of energy since it can be used to produce electricity, heat, but also liquid and gaseous fuels (McKendry, 2002a). Furthermore, biomass can be stored and energy can be produced on demand, contrary to other renewable sources of energy such as solar and wind, which are characterized by intermittency.

Biomass energy plays a crucial role in climate change mitigation as emphasized in the IPCC Special Report on Renewable Energy Sources: relying more heavily on certain technological options such as perennial cropping systems, the use of biomass residues and wastes and advanced conversion systems could reduce emissions by 80 to 90% compared to the fossil energy baseline scenario (Chum et al., 2011).

This paper focuses on bioenergy technologies that convert biomass into electricity via thermochemical or biochemical conversion paths. Given the relevance of these technologies, we assess their potential and future costs. The production of liquid biofuels for the transport sector has been the object of a separate investigation (Fiorese et al., 2013).

For bioenergy to play a significant role in the coming decades, several issues must be addressed. First, biomass resources are scarce. Their widespread use could lead to high demand for feedstock and raise concerns with respect to the social and environmental sustainability of its supply, the potential competition for land with food production (Dornburg et al., 2008; Tilman et al., 2009), the threat for biodiversity and soil fertility (Lal, 2005), and the consequences on forests' carbon sinks (Böttcher et al., 2012). Recent research shows that land use and land cover changes driven by biomass production for energy purposes may negatively impact the life cycle GHG emissions balance (Gelfand et al., 2011; Fargione et al., 2008; Searchinger et al., 2008).

Second, the cost of electricity from biomass is generally high, not competitive with the cost of electricity from fossil sources unless some form of financial support is in place (IEA, 2012a). Bio-electricity costs depend on the specific conversion

process, the nature and cost of the feedstock, as well as plant size. When low cost feedstocks are available, plant scale is large and co-generation is viable,¹ the costs of electricity from biomass can be competitive. Unfortunately, today these conditions are realized only in a very limited number of cases.

Assuring the continuity and the quality of biomass supply, improving the efficiency of conversion plants, and building advanced conversion plants with innovative technologies are some of the possible ways to decrease the costs of electricity from biomass while addressing the environmental and social concerns highlighted above (IEA, 2012a; Baxter et al., 2011; Bauen et al., 2009; Farrell and Gopal, 2008).

Research, Development and Demonstration (RD&D) funding is expected to increase the efficiency of bioenergy technologies and to reduce their cost. However, the role of future RD&D in bioenergy competitiveness and commercial success is uncertain. Moreover, given the great variety of feedstocks and the different level of maturity of the various technological options, each technological path will require a different focus of RD&D spending, namely basic research, applied research or demonstration.

To better understand the potential contribution of bioenergy and the role of RD&D in fostering the development of bioenergy technologies, we surveyed sixteen leading experts in this sector. The group of respondents was very diverse, with experts from different EU Member States and with different professional backgrounds (private sector, academia, institution). The outcomes of this research include probabilistic information on the future costs of electricity produced from biomass and on the potential role of RD&D in reducing these costs.

¹ Viable cogeneration means that most of the heat co-produced is used.

This paper contributes to the literature by providing novel evidence on the likely evolution of biomass electricity costs in the coming decades and on the range of uncertainty surrounding them. We thus complement the insights obtained from energy system models such as POLES (IPTS, 2010) or integrated assessment models such as WITCH (Bosetti et al., 2006). Moreover, we elicited the experts' opinions on future bioenergy diffusion scenarios by extensively discussing possible barriers and the most effective solutions to overcome them. Therefore, the analysis of the experts' data results in a number of important policy recommendations that can guide future RD&D choices and the commitment of the EU and its Member States in supporting biomass technologies.

The next section of the paper reviews the current status of bioenergy technologies. Section 3 describes the expert elicitation process. Section 4 presents the experts' assessment of the current status of biomass technologies. Section 5 illustrates the experts' projections of the cost of electricity from biomass under five different RD&D funding scenarios. Section 6 discusses the likely diffusion of bioenergy in the market. We focus on (i) the regions that will most likely achieve cost-competitiveness first, (ii) the potential barriers to bioenergy success, (iii) the possible negative externalities associated with biomass technologies and (iv) the dynamics of knowledge spillovers and technology transfer. The last section of the paper concludes and discusses the main findings of the study.

2 Bioenergy today

Biomass is the largest renewable energy source worldwide² (IEA, 2012c), but its use differs significantly by region. In Africa 47.8% of the 2010 total primary energy supply came from biomass (328 Mtoe of 686 Mtoe), while in OECD countries the corresponding figure was 4.5% (242 Mtoe out of 5,406 Mtoe; IEA, 2012c). In developing countries, biomass technologies are typically characterized by very low efficiencies, and in some cases severe impacts on human health (i.e. biomass use in domestic stoves or fireplaces). On the contrary, advanced technologies are available in more developed countries, where biomass is primarily used to produce electricity.

In the EU27, the contribution of solid biomass and biogas to the 2010 gross electricity production was however rather small, roughly 3% of 3,345 TWh (European Commission, 2012).³ The most important energy sources, namely nuclear and coal, account for a much larger share (27% each), followed by natural gas and hydro (24% and 12%, respectively).

Notwithstanding this limited contribution to current electricity supply, biomass is one of the energy sources that the European Commission plans to further support to

² In 2010, world total primary energy supply was 12,782 Mtoe, of which 13% (1,657 Mtoe) was produced from renewable energy sources with the following shares 9.8% biofuels and wastes, 2.3% hydro, 0.9% geothermal, solar, wind, heat and others (IEA, 2012c). In 2010, 1.3% (279 TWh) of world electricity generation (21,431 TWh; IEA, 2012b) was produced from biofuels and waste, while in OECD countries this figure was 2% (215 TWh out of 10,744 TWh of total gross electricity generation; IEA, 2011). According to IEA definitions, biofuels and waste include solid biofuels, liquid biofuels, renewable municipal waste and biogases.

³ The total gross electricity produced from solid biomass in 2010 in EU27 was 69.9 TWh (EurObserv'ER, 2012). Germany, Finland and Sweden are the countries with the highest production of electricity from solid biomass, each with about 10 TWh. The contribution of biogas was also relevant: in 2010 it accounted for 30.3 TWh of total gross electricity production (EurObserv'ER, 2012). More than half of this electricity (16.2 TWh) is produced in Germany, where biogas has experienced an incredible development in the recent years. Other EU27 countries contribute with much smaller amounts of electricity from biogas: the United Kingdom with 5.7 TWh, Italy with 2.1 TWh and all other countries with 1 TWh or less (EurObserv'ER, 2012).

address the rising climate and energy concerns. Directive 2009/28/EC sets legally binding shares of renewable energy in gross final energy consumption for each EU Member State, in line with the Climate and Energy Package (COM/2008/30). To comply with these requirements by 2020, in 2010 each EU Member State submitted a National Renewable Energy Action Plan to the European Commission specifying how each member would raise its share of renewable energy sources. Altogether, these plans imply that in 2020 solid and gaseous biomass for heating, cooling and electricity will supply about 46% of the EU renewable targets (110 out of 240 Mtoe) and 9.4% of total EU final energy consumption (Beurskens et al., 2011). In practice, meeting these targets means raising biomass electricity production in the EU from about 104 TWh in 2010 to 232 TWh by 2020 (Beurskens et al., 2011). This increase can be achieved only if more efficient or novel biomass conversion technologies become commercial and if bioenergy production costs are reduced.

As already mentioned, biomass is a versatile resource and can be converted to energy via several conversion routes. Some of the most relevant factors in choosing a specific conversion route are the nature of the feedstock, the availability of a given technology and the demand for a specific energy product, namely electricity, heat or fuels (McKendry, 2002b, 2002c; Bauen et al., 2009). Some biomass technologies are in principle able to adapt to different feedstocks and to produce different energy products. Some technologies that could be used to convert biomass to commercial energy are already available in other sectors (e.g., Organic Rankine Cycles, ORC, and pyrolysis are well proven for geothermal applications and for

niche applications in the food industry respectively), but still need to be adapted to bioenergy applications.

Biomass conversion technologies are therefore diverse and characterized by different stages of development and deployment. Combustion and gasification of biomass are key conversion technologies for the production of power and combined heat from solid biomass. Co-firing biomass with coal is a well proven means to use biomass and exploit scale efficiencies of a coal plant. Fast pyrolysis allows the production of a bio-oil with higher energy density than the original feedstocks, thus improving handling, storage and transport. The key conversion technology for animal wastes and other high-moisture content materials is anaerobic digestion for biogas production.

Table 1 synthetically reviews the current state of the main biomass conversion technologies. The key parameters the literature focuses on are efficiency, scale of plant, technology-specific issues, and development state⁴. We also report the cost of electricity produced with each specific technology (Bauen et al., 2009; Baxter et al., 2011; Chum et al., 2011; IEA, 2012a).

Electricity costs vary significantly: direct co-firing in coal plants is within the lower range of 3-5.5 cUSD/kWh⁵, while anaerobic digestion is in the higher range of 16-22 cUSD/kWh. Overall, costs vary from a minimum of 3 cUSD/kWh for direct co-firing to a maximum of 25 cUSD/kWh for ORC. The current and projected costs of electricity from biomass for different plant scales provided by the IEA Bioenergy Roadmap (IEA, 2012a) generally lie in the high range (Table

⁴ However, since many developments are taking place in industry and are not often documented in the literature, it is difficult to classify precisely the development state of each technology in Table 1 (Chum et al., 2011).

⁵ Costs are always expressed as 2005 USD.

1). Specifically, current costs for biomass co-firing are estimated around 6.9-12.2 cUSD/kWh. The cost range for large scale plants (between 50 and 100 MW capacity) is around 10.4-21.7 cUSD/kWh. Costs and plant scale are inversely correlated: for medium applications (10-50 MW) the range is 10.4-21.7, while for small scale applications (<10 MW) it is 11.3-37.3 cUSD/kWh. Regarding future projections, the IEA foresees a 19% average reduction for the lower range and a 25% average reduction for the higher range by 2030⁶.

Within Europe, the development of the bioenergy sector is fostered through the 7th Framework Programme, the European Biofuels Technology Platform and the European Bioenergy Industrial Initiative, which was launched in 2010⁷. The total public RD&D budget devoted to biomass (liquids, solids and biogas) increased from about 100 Million USD in 2002 to roughly 470 Million USD in 2010 (Figure 1; IEA, 2012d). This corresponds to about 8% of the total 2010 EU energy technology RD&D budget⁸ (5,963 Million USD), or 30% of the budget allocated to renewable energy sources (1,517 Million USD). As for biomass (liquids, solids and biogas), in the period 2002-2010 the average budget allocation was 25% for applications for heat and electricity, 23% for the production liquid biofuels, 13% for the production of solid biofuels, 12% for other biofuels, only 1% for biogases; while the rest was not specifically allocated.

⁶ Precisely, 2030 expected costs for electricity from biomass are: 5.2-8.7 c€/kWh for co-firing; 7.8-13.9 c€/kWh for large scale plants (50-100 MW); 6.1-20 c€/kWh for medium scale plants (10-50 MW); 9.5-31.2 c€/kWh for small scale plants (<10 MW) (IEA, 2012a).

⁷ <http://www.biofuelstp.eu/eibi.html>.

⁸ Between 2002 and 2010, the average RD&D budget for all energy technologies in the EU (4,109 Million USD) was allocated as follows: energy efficiency 18%, fossil fuels 11%, renewable energy sources 20%, nuclear 32%, hydrogen and fuel cells 4%, other power and storage technologies 6% and other cross-cutting technologies/research 7% (IEA, 2012d).

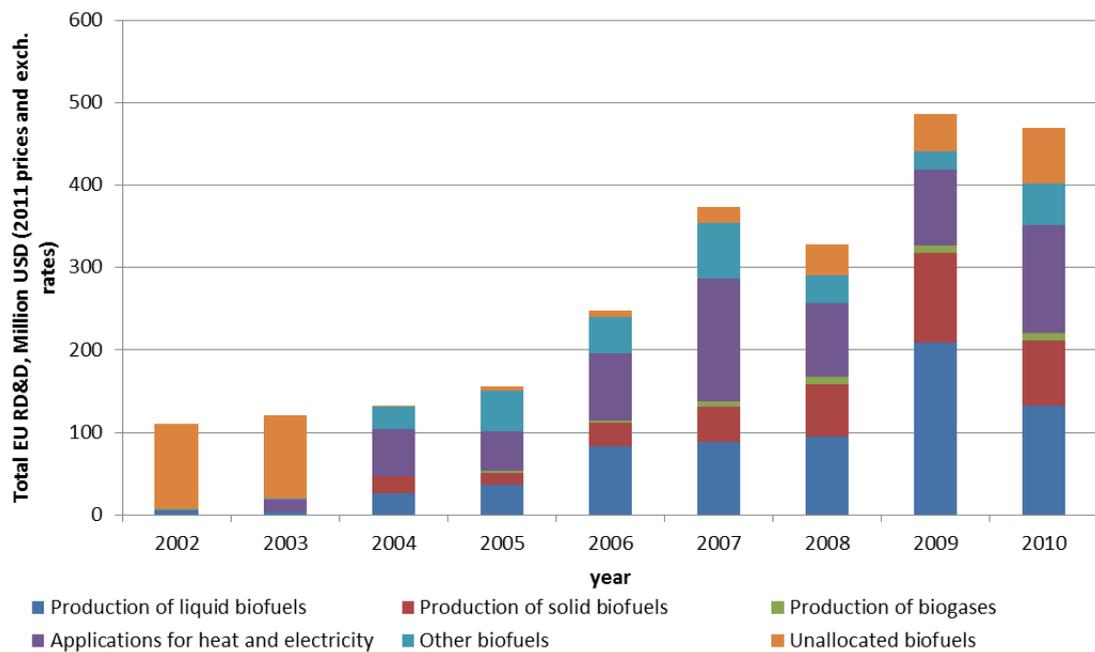


Figure 1: EU public funding for biofuels technologies, 2002-2010 (IEA, 2012d).

Each organization supporting biomass development focuses on the importance of specific short term and long term targets. According to the European Bioenergy Industrial Initiative, the main barriers to the success and diffusion of bioenergy technologies can be overcome if demonstration projects are supported at the relevant scale for each technology. On the other hand, the Bioenergy Technology Roadmap of the SET-Plan (European Commission, 2009) stresses the importance of making the most promising conversion technologies commercially available, of assessing the sustainable biomass supply on different time horizons and committing to a clear R&D program beyond 2020. Finally, the IEA roadmap (2012a) states similar targets but also stresses that effort should be made to reduce trade barriers for feedstocks and to enhance international exchange of technology and deployment.

Table 1: Efficiency, current cost of electricity, scale of plant, development state of the main conversion technologies for producing electricity from solid biomass and biogas (used acronyms: Organic Rankine Cycle, ORC; Combined Heat and Power, CHP; Integrated Gasification Combined Cycle, IGCC; Bauen et al., 2009; Baxter et al., 2011; Chum et al., 2011; IEA, 2012a).

Technology	Efficiency [♦]	Cost of electricity (cUSD/kWh)	Scale of plant	General issues	Development state
Combustion + steam cycle	15-30%	7-9 [♦] 10.4-21.7 (large) [▼] 6.9-24.3 (medium) [▼] 11.3-37.3 (small) [▼]	Viable for large scale (30-100MW) Recent development of small scale applications	Reliable technology Difficult biomass procurement for large scale	Commercial
Combustion + Stirling engine	Around 30%	15-24 [♦]	Micro scale application (10-100kW)		Demonstration
Combustion + ORC	16-20%	11-25 [♦]	Small scale (0.5-2MW)	Few ORC plants operate on biomass. Need to improve efficiency and reliability, and to reduce costs.	Demonstration/ Early commercial
CHP plants (biomass based)	High Overall 70-90%	7.5-13 [♦]	Scale is limited by heat demand and its seasonal variation	Need to find an economic application for waste heat	Commercial
Gasification + gas engine	22-35%	6.5-8 [♦] 10-14 [♦]	High efficiency also at small scale (0.01-10MW)	Complex technology Reliability and efficiency must be proven	Demonstration/ Early commercial
Gasification + IGCC	Up to 42%	10.5-13.5 [♦]	High efficiency also at large scale	Complex technology Reliability and efficiency must be proven	Demonstration
Direct co-firing	35-45% (at 10% biomass on energy base)	3-5.5 [♦] 2.9-5.3 [♦] 6.9-12.2 [▼]	Cost-effective	Because of biomass varying characteristics, there are limits to the amount of biomass that can be co-fired Possible impacts on plant operation and lifetime	Commercial
Fast pyrolysis	80% (conversion efficiency of biomass in bio-oil)	7-15 [♦]	-	Bio-oil is cheaper to handle, store and transport. High energy density	Basic and Applied R&D/ Demonstration
Anaerobic digestion + biogas in CHP	32-45%	16-22 [♦]	Decentralized farm-sized units (0.25-2.5MW)	Feedstocks are manure, slurries and sewage. Co-feeding agricultural residues and crops increases efficiency	Commercial

[♦] Baxter et al., 2011; [♦] Bauen et al., 2009; [♦] Chum et al., 2011; [▼] IEA, 2012a.

3 The expert elicitation survey

We developed a survey to elicit experts' judgments on the future potential of bioenergy technologies. Precisely, the survey was designed to shed light on the future role of bioenergy technologies, to understand how a variation in the level of public RD&D funding would affect future production costs of electricity from biomass and to assess the expected diffusion of bioenergy technologies. Figure 2 provides a graphical representation of the bioenergy technologies assessed in the survey.

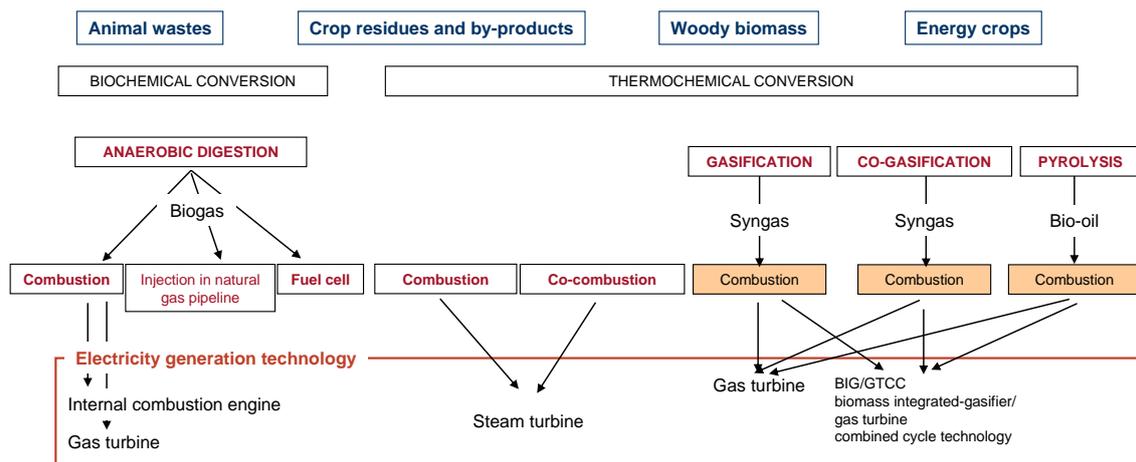


Figure 2: Technology paths that have been assessed in the interviews with the experts

Collecting information from experts through elicitation protocols is an increasingly applied research technique, particularly useful to overcome the lack of historical data and to manage complex and uncertain issues. Expert elicitation has been recently applied to investigate the uncertain effects of RD&D investments on the prospect of various energy technologies: carbon capture and storage (CCS; Chan et al., 2011; Baker et al., 2009a), hybrid electric vehicles (Catenacci et al., 2012; Baker et al., 2010), solar

PV technologies (Bosetti et al., 2012; Baker et al., 2009b; Curtright et al., 2008), cellulosic biofuels (Fiorese et al., 2013; Baker and Keisler, 2011). Kretschmer and Bennett (2011) surveyed experts' opinions on electricity from biomass technologies and their future potentials.

Our survey on biomass technologies is part of a systematic collection of experts' estimates for Europe carried out within the ERC-funded ICARUS project,⁹ which included analyses on solar technologies (Bosetti et al., 2012), on nuclear energy (Anadón et al., 2012), on biofuels (Fiorese et al., 2013), and on batteries for electric drive vehicles (Catenacci et al., 2012). The structure of the elicitation process developed within this project was defined following the analyses of the protocols and of the resulting guidelines from the vast literature on decision analysis (Clemen and Reilly, 2001; Keeney and von Winterfeldt, 1991; Meyer and Booker, 1991; Morgan and Henrion, 1990; O'Hagan et al., 2006; Phillips, 1999). The accurate design of the elicitation protocol was aimed at minimizing the risks of errors or biases in the experts' estimates, and started with a careful choice of the elicitation situation, with the structuring of questionnaires and with face-to-face interviews. Table 2 schematically shows the structure of the elicitation protocol and of the questionnaire.

One particularly important characteristic of the elicitation protocol was the selection of a set of experts¹⁰ (listed in Table 1) who covered a wide range of background knowledge on bioenergy technologies and belonged to different professional sectors (academia, institutions and private sector). All answers are anonymously reported in the

⁹ www.icarus-project.org.

¹⁰ We assessed the level of expertise of each selected expert considering tangible evidence such as publications and direct involvement in projects related to research and development of bioenergy technologies. A first group of experts was selected according to the above exposed criteria, and they were asked to point out other experts to involve in the elicitation exercise, according to the so-called "snowball sampling technique" (Salganik and Heckathorn, 2004; Giupponi et al., 2006).

rest of the paper and the order of the experts does not reflect the one in Table 1. Pilot interviews were carried out to test the whole elicitation process and to eventually modify parts of the questionnaire. During each interview, the experts were first briefed on the project's purpose and then warned about the occurrence of specific heuristics or biases in the estimates.

Table 2: Elicitation protocol and structure of the questionnaire.

Introductory Phase					
Definition of the elicitation subject	Choice of the elicitation situation and modes	Experts selection and engagement	Pilot tests	Modification of questions	
Background Information					
Motivational letters and statement of informed consent	Technology efficiency and cost, trend of RD&D investments and costs	Bias and overconfidence, use of percentiles			
Elicitation Phase					
Self-assessment of expertise	Evaluation of the status of the technology	RD&D budget allocation	Cost of electricity under different funding scenarios	Knowledge spill-overs and externalities	Diffusion

For more detailed information on the protocol structure and on the techniques applied to control and detect bias occurrence, please refer to Bosetti et al. (2012) and to Fiorese et al. (2013). Surveys were carried out in 2011. Follow-up interviews also allowed us to check the elicited information, to deepen the discussion with each expert, and, when necessary, to correct possible inconsistencies.

Table 3: List of experts participating in the survey

Name and Surname	Affiliation	Country	Expertise
Alessandro Agostini	JRC - Joint Research Centre	Netherlands	Policy
Göran Berndes	Chalmers University of Technology	Sweden	Energy system
Rolf Björheden	Skogforsk - the Forestry Research Institute of Sweden	Sweden	Energy system
Stefano Capaccioli	ETA - Florence Renewable Energies	Italy	Energy system
Ylenia Curci	Global Bioenergy Partnership	Italy	Policy
Bernhard Drosig	BOKU - University of Natural Resources and Life Science	Austria	Technology
Berit Erlach	TU Berlin - Technische Universität Berlin	Germany	Technology
Andre P.C. Faaij	Utrecht University	Netherlands	Energy system
Mario Gaia	Turboden s.r.l.	Italy	Technology
Rainer Janssen	WIP - Renewable Energies	Germany	Energy system
Jaap Koppejan	Procede Biomass BV	Netherlands	Technology
Esa Kurkela	VTT - Technical Research Centre of Finland	Finland	Technology
Sylvain Leduc	IIASA - International Institute for Applied Systems Analysis	Austria	Energy system
Guido Magneschi	DNV KEMA	Netherlands	Technology
Stephen McPhail	ENEA - Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	Italy	Technology
Fabio Monforti-Ferrario	JRC - Joint Research Centre	Italy	Policy

The first step in our elicitation process was to ask experts to self-evaluate their expertise on the different bioenergy feedstocks and technologies on a scale from 1 (low) to 5 (high). The results of this exercise are reported in Figure 3. Most experts declared to possess a good knowledge with respect to several bioenergy technologies and a thorough outlook of the whole bioenergy sector. At least one expert declared a high level of expertise for each of the technologies included in the survey, with woody biomass and energy crops feedstocks and the conversion processes of biomass into electricity (such as combustion and gasification) displaying the highest level of expertise in our sample.

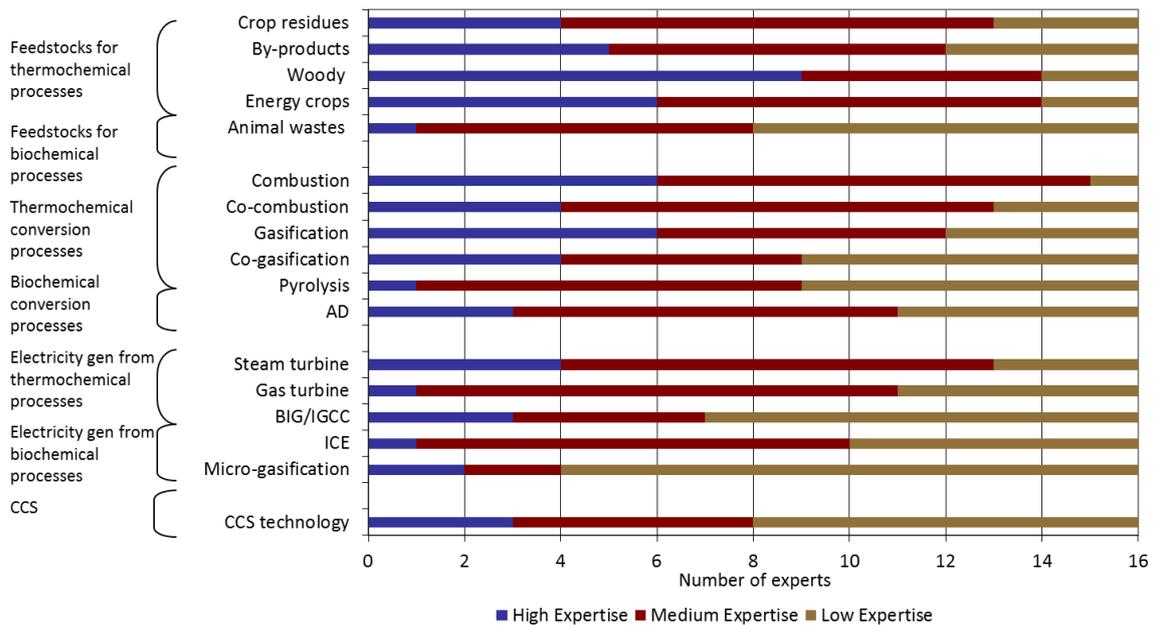


Figure 3: Distribution of the experts in three classes of expertise with respect to all the technological paths. Experts self-ranked on a Likert scale from 1 to 5. Here, high expertise is assigned if an expert declared a level of knowledge >3; medium expertise if the level of knowledge =3; low expertise if the level of knowledge <3. (AD stands for Anaerobic Digestion; BIG/IGCC stands for Biomass Integrated-Gasifier/Integrated Gasification Combined Cycle; ICE stands for Internal Combustion Engine; CCS stands for Carbon Capture and Storage).

4 Technical development of bioenergy technologies and budget allocation

In the first part of the survey, experts assessed the level of maturity of each technological option included in Figure 1 (feedstocks, conversion processes and generation technologies) and listed the main technical barriers hindering their development. These questions set the stage for the subsequent elicitation of costs as they forced experts to carefully think through all the technological bottlenecks hindering commercial success.

Figure 4 reports aggregate data on the current status of each technology, grouped in seven main classes: feedstocks, conversion processes and electricity generation for the

biochemical and thermochemical conversion paths, and CCS. The size of each circle represents the number of experts providing a given assessment for the specific process. Table 4 reviews the main technical barriers identified during the interviews.¹¹

Woody biomass emerges as the most advanced feedstock, even though improvements in the logistics of biomass procurement are still needed. The efficient and sustainable use of crop residues and by-products are both deemed in need of advances, mostly due to the challenges of handling variable materials with diverse elementary composition and quality. Energy crops still face technical barriers, namely the development of sustainable farming practices (e.g., water, fertilizer, pesticide needs), and socio-political barriers such as the competition for land with food crops. Animal waste, which is a feedstock for the biochemical conversion route in which half of the experts declared a low level of expertise, emerges as still in need of technical advances.

Thermochemical conversion processes include some technologies which are well developed as well as others which are emerging. For these technological paths, combustion and co-combustion of biomass with coal are deemed to be mature technologies (12 and 6 experts, respectively), although improvements specifically aimed at increasing the conversion efficiency and at reducing the atmospheric emissions were suggested. 11 and 8 experts respectively agreed that gasification and co-gasification of biomass with coal are two technologies that still need advances, specifically referring to up-scaling for both processes. According to 8 experts, substantial advances are needed in order to make pyrolysis a successful technology: the scarce quality of bio-oil emerges as an important barrier to its development. Conversely, the biochemical conversion

¹¹ To select only the main barriers, we chose to list the factors indicated by at least three experts (e.g. for the “animal waste” feedstock, few experts chose to indicate possible barriers, and there was no agreement on them).

process, anaerobic digestion, is still in need of some advances according to 7 out of the 8 experts who assessed this specific technological path.

Overall, fewer experts chose to assess the development of the electricity conversion processes, for which the pattern of non response was generally higher than for upstream process of biomass production.¹² This indicates that the pool we selected was mostly experienced in the upstream process of biomass production (Figure 3). Technologies that are used to produce electricity in the thermochemical pathway are considered either to be mature (steam turbines and gas turbines), or still needing advances (Biomass Integrated-Gasifier/Integrated Gasification Combined Cycle, BIG/IGCC). Conversely, technologies for electricity production in the biochemical path are less developed, according to the experts. Conversion of biogas, the product of anaerobic digestion, into electricity through micro-gasification or its injection in the natural gas grid still need advances. Finally, 9 experts stated that CCS applied to bioenergy technologies needs advances that, furthermore, are substantial for six experts.

Few experts chose to add to their analysis specific technologies which were not originally selected as part of the survey. The process of torrefaction was mentioned by five experts who evaluated its status as in need of substantial advances, since the technology still has to be demonstrated. Organic Rankine Cycle was mentioned by three experts and was evaluated as a technology needing further improvements.

¹² The highest number of no responses is related to the biochemical pathway (animal wastes, anaerobic digestion, micro-gasification and injection of biogas in the natural gas grid)

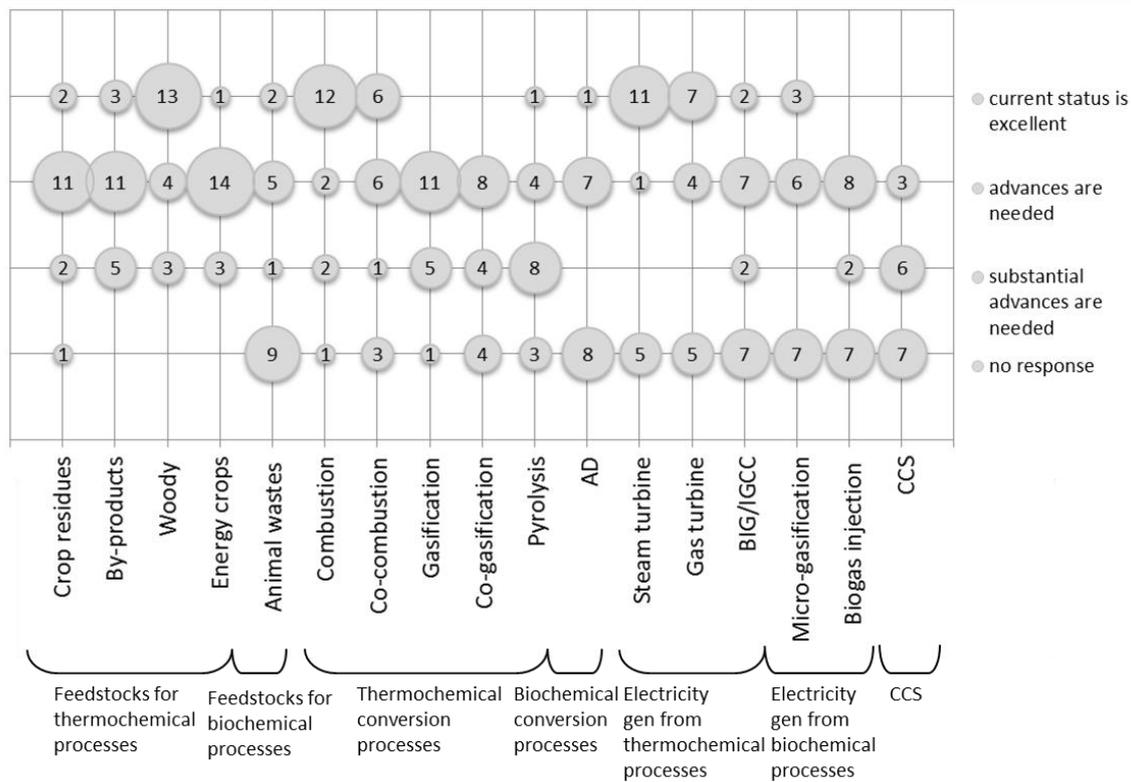


Figure 4: Number of experts evaluating the status of each technology as excellent, needing advances or substantial advances; the number of experts who did not answer is also shown for each technology (AD stands for anaerobic digestion, Biogas injection stands for injection of biogas in the natural gas grid).

In light of their assessment of current technological status, experts were asked to choose the optimal 2010-2030 RD&D budget allocation, namely the one that would maximize the probability that bioenergy technologies be commercially successful by 2030. Each expert was asked to allocate 100 chips, corresponding to 162.1 million¹³ 2007USD, the 2002-2009 average annual public RD&D investments of EU members. Results are shown in Figure 5. One expert chose not to participate in this exercise.

¹³ On the basis of IEA definitions (IEA, 2012d), we assume that RD&D for bioenergy is given by the sum of the RD&D allocated to Production of solid biofuels, Production of biogases, Applications for heat and electricity, Other biofuels and Unallocated biofuels.

Table 4: Keywords mentioned by at least three experts.¹²

Feedstocks for thermochemical processes	Crop residues	Logistic issues Issues related to elementary composition
	By-products	Issues related to elementary composition and quality
	Woody	Logistic issues
	Energy crops	Logistic issues Sustainability issues Competition for land
Thermochemical conversion processes	Combustion	Mature technology Increase efficiency Reduce emissions
	Co-combustion	Mature technology (especially for low shares of input biomass) Increase efficiency Reduce emissions
	Gasification	Up-scaling (economies of scale) Input fuels (must be proven for different feedstock, issues related to scarce homogeneity of input fuels)
	Co-gasification	Up-scaling (economies of scale)
	Pyrolysis	Improve oil quality
Electricity generation from thermochemical processes	Gas turbine	Need to be adjusted to syngas
Electricity generation from biochemical processes	Injection of biogas in the natural gas grid	Gas cleaning

Eight out of fifteen experts allocated some funding to all of the technological paths, six supported at least 6 out of the 7 technologies, and only one expert decided to split up the budget between only 4 of the seven available options.

Notwithstanding the experts' self-declared better knowledge of the upstream stages of electricity from biomass production, the budget was used to support all stages of the production process. Feedstock were allocated 27% of the total budget (10% to biochemical and 16% to thermochemical paths), conversion processes 38% (11% to biochemical and 27% to thermochemical paths), electricity generation technologies 27% (12% to biochemical and 15% to thermochemical paths) and CCS the remaining 8%¹⁴..

¹⁴ Note that the experts were asked to allocate the budget to macro-categories such as, for example, feedstocks for thermochemical processes and for biochemical processes, etc. However, some macro-
(footnote continued)

On average, experts allocated 16.5 and 10.3 chips to feedstocks suitable for the thermochemical and the biochemical path, respectively. There is some variation in budget allocated for the biochemical path: 6 experts allocated 8 chips or less and the remaining ten experts allocated between 10 and 25 chips. As for the thermochemical path, four experts allocated 20 or more chips, while the remaining eleven experts allocated between 8 and 15 chips.

The highest average budget allocation was devoted to improving thermochemical conversion processes. In particular, experts agreed on allocating more than one fourth of their budget to those processes (27 chips on average). On the other hand, experts assigned to biochemical conversion processes about 11 chips each.

Electricity generation processes also received a good share of the RD&D budget. On average experts allocated 15 and 12.4 chips for the thermochemical and the biochemical paths, respectively. For the thermochemical paths, five experts allocated 20 or more chips to these technologies, while the remaining devoted between 5 and 15 chips. For the biochemical paths, experts are even more divided: a group allocates a high share of the budget (25-32 chips) while the other group allocates a low number of chips (less than 15).

Finally, there is scarce agreement among the experts about the budget that should be allocated to CCS applied to bioenergy technologies. Five experts did not allocate any chip at all. Among the ten experts who assigned part of their budget to CCS, seven of them devoted 10 chips or less, while the remaining three allocated more, i.e. 15, 20 and 25 chips.

categories include several sub-categories, as emerges e.g. from Figure 3, while other macro-categories only consider one single option (e.g. animal waste in feedstock for biochemical processes). The results of the allocation exercise could also reflect this difference among macro-categories.

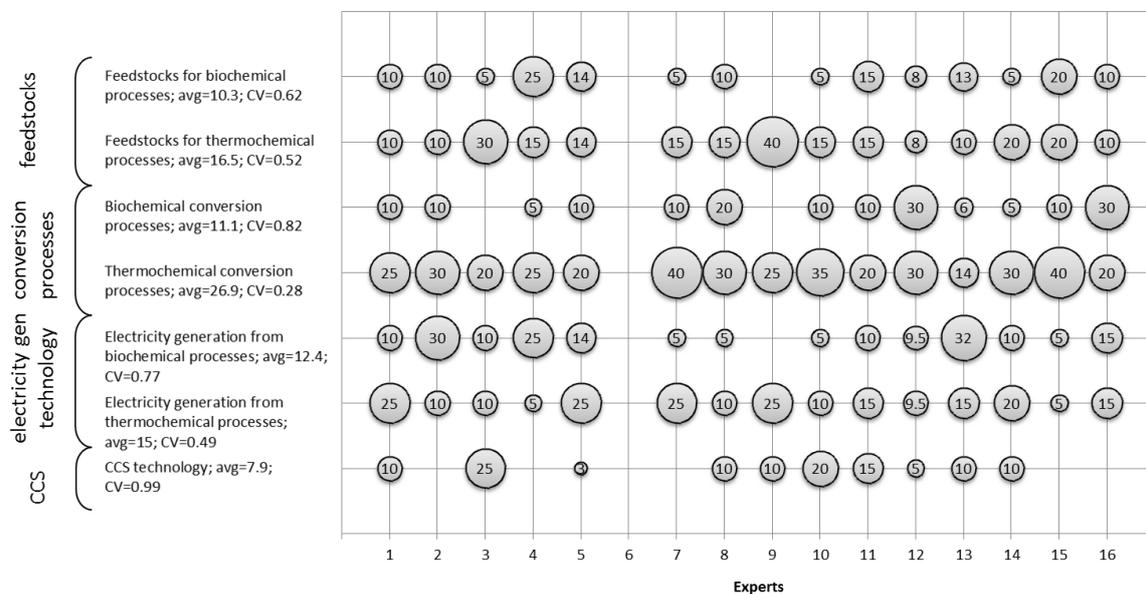


Figure 5: Allocation of the RD&D budget over the 2010-2030 timeframe to make bioenergy technologies commercially successful in 2030. The budget is conventionally expressed in 100 “chips” per expert (column), to be distributed among the different technologies. For each technology, both the average and coefficient of variation in chips allocation are provided.

Experts suggested that the type of RD&D for each of the technological paths should be different (Figure 6). Basic research is needed for CCS (33% of the allocated budget) and for conversion processes in both the thermochemical (21%) and the biochemical (18%) paths. However, basic research plays a much smaller role for all other technologies, namely between 6 and 13% of the allocated budget. Applied research is extremely important for all technologies: its share of the allocated budget for each technology ranges between 39% (electricity generation for the thermochemical path) and 75% (biochemical feedstocks). Finally, experts allocated a significant number of chips to demonstration activities, ranging from 18% for biochemical conversion processes and 53% for the thermochemical path.

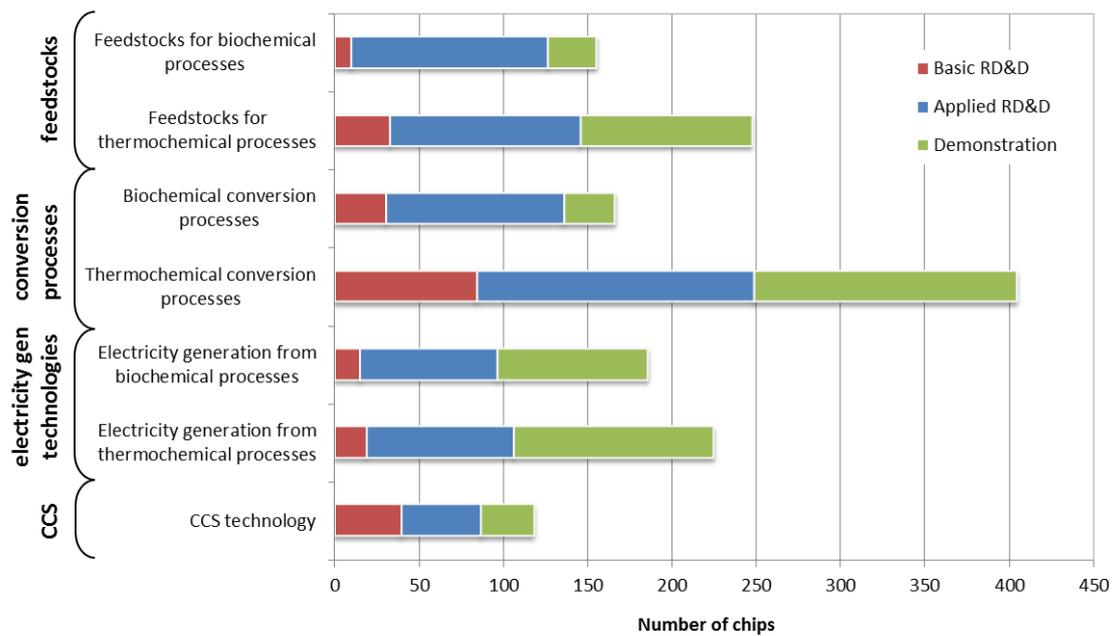


Figure 6: Sum of the RD&D allocated by all experts among different technologies and breakdown of the budget among basic, applied and demonstration RD&D.

5 RD&D effectiveness on future electricity cost from bioenergy technologies

Core of the survey was to assess if, and under what conditions, the costs of electricity from bioenergy can become competitive with conventional fossil electricity, in the absence of other specific supports. To this end, we elicited the experts' opinion on the probabilistic future costs of electricity from biomass. Given the importance of RD&D investment in securing further cost reductions, we asked the experts to provide cost estimates under five different RD&D funding scenarios. In the first scenario, the current level of public investment in RD&D for bioenergy (161.1 million 2007USD) is assumed constant until 2030.¹⁵ The second and third scenarios considered a +50% and +100%

¹⁵ We asked the experts to consider 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 2005 Euros and Dollars.

increase in the RD&D budget over the whole period, respectively. In the fourth and fifth scenarios RD&D funding over the whole period was decreased by 50% and 100% RD&D, respectively. The final scenario effectively set the public RD&D biomass budget to zero.

Experts were told that the only variable changing across the scenarios was public EU funding, while private funding as well as other countries' RD&D programs remained the same. Furthermore, we specifically asked the experts to assume no additional incentive or subsidy for biomass electricity production.

To avoid anchoring effects and to minimize naturally occurring errors or biases in the experts' estimates, we structured this section of the questionnaire in two parts. In the first one, experts were asked to provide the 90th, 10th and 50th percentiles of the future cost of electricity from bioenergy in 2030 under different RD&D investment scenarios. In the second part, we asked each expert to estimate the probability that, conditional on each of the RD&D investment scenarios, the cost of electricity from bioenergy in 2030 would be lower than three cost targets: 11.27, 5.55 and 3 cUSD/kWh.¹⁶ The double elicitation question allowed us to investigate in greater depth the experts' opinion, stretch his/her potential overconfidence and test for reaction to possible inconsistencies.¹⁷

¹⁶ The three different "breakthrough" cost levels 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 projected cost of electricity from traditional coal power plants in 2030, in the presence of a specific policy to control CO₂ emissions (thus effectively increasing electricity costs from fossil sources). Specifically, we assumed a carbon price accounting for more than half of the cost of electricity (5.8 cUSD/kWh), which is in line with a 550ppm CO₂ only stabilization target by 2100 (according to projection of the WITCH model in Bosetti et al., 2009). The second breakthrough cost (5.55 cUSD/kWh) is the projected cost of electricity from traditional fossil fuels in 2030, without considering any carbon tax. Finally, the third breakthrough cost (3 cUSD/kWh) assumes that bioenergy might become competitive with the levelized cost of electricity from nuclear power.

¹⁷ Since experts typically think in terms of technological endpoints and not in terms of costs, we provided them with a formula deriving the cost of electricity from specific technical factors, such as feedstock costs, efficiency, capital costs and operational and maintenance cost. Experts who did not feel at ease with *(footnote continued)*

Future costs under the different RD&D funding scenarios are reported in Figure 7 and Figure 8. The elicited costs indicate a high degree of uncertainty and variance among the experts. These in turn derive from the fact that each expert referred to a different technology or to a mix of technologies when providing cost estimates. Moreover, each expert made different assumptions on key variables, such as feedstock characteristics or plant scale.

Experts are clustered in two groups. The first is composed of Experts 2 to 9, who considered a mix of bioenergy technologies and by Expert 10 who provided the cost of electricity for cogeneration and gasification with synthesis of syngas. This cluster of experts provided relatively optimistic estimates compared to those of the second group (Experts 11, 12 and 13, extreme right in Figure 7) who indicated their costs specifically for the biochemical route.

Expert 1 emerges as an outlier: the estimates refer to a mix of technologies but are much higher than those of other experts.¹⁸ Since Expert 1 clearly expressed his/her pessimism regarding the potential of the technology per se, we chose not to include his/her values in the average estimates and in the subsequent description of results.

Excluding Expert 1, the average best estimate (50th percentile) of bioenergy cost in 2030, under current RD&D funding, is 10.8 cUSD/kWh. The aggregate statistics show that experts are convinced that RD&D investments will strongly influence the cost of electricity from biomass in the future. The average best estimate of cost is 11% and 17% lower in the +50% and +100% scenarios, respectively. Smaller RD&D budgets would

directly providing monetary estimates, were free to use the formula to estimate how improvements in technical factors would result in lower monetary costs.

¹⁸ His/her best estimate is 23 cUSD/kWh under the business as usual scenario.

result in higher costs: the -50% and -100% budget scenarios increase the experts' average best estimate by 14% and 23%, respectively.

The estimated costs are very different for the two clusters described above: costs provided by the first group range from as low as 4.4 cUSD/kWh to as high as 13 cUSD/kWh.¹⁹ These values are significantly lower compared to the best estimates of the second group of experts, which span from 12.5 to 22.5 cUSD/kWh.

Notwithstanding the lower best guesses for the business as usual R&D scenario, the first group of experts assigns relatively lower marginal returns to RD&D investment, as the +50% and +100% funding scenarios have lower impact on their expected costs compared to those of the second group: best estimate decrease by 8% and 14% in the +50% and +100% RD&D scenarios, respectively. Cost reductions could be achieved mainly in presence of an increase in the scale of plants and a full scale market deployment, and thanks to learning-by-doing effects. However, as the experts point out, large scale deployment of bioenergy would imply more biomass needed (with consequences on the agricultural market) and thus higher costs of feedstock supply. Moreover, if biomass becomes a global commodity, meeting sustainability requirements will increase biomass costs and, as a consequence, the cost of electricity.

Conversely, the second group of experts is more confident on the positive role of RD&D investments on costs: the average expected reductions of costs are 16% and 25% in the +50% and +100% RD&D scenarios, respectively.

¹⁹ The most optimistic in the pool of experts, Expert 10, provided costs estimates specific for Northern Europe and also assumed profits derived from selling the heat co-produced with electricity.

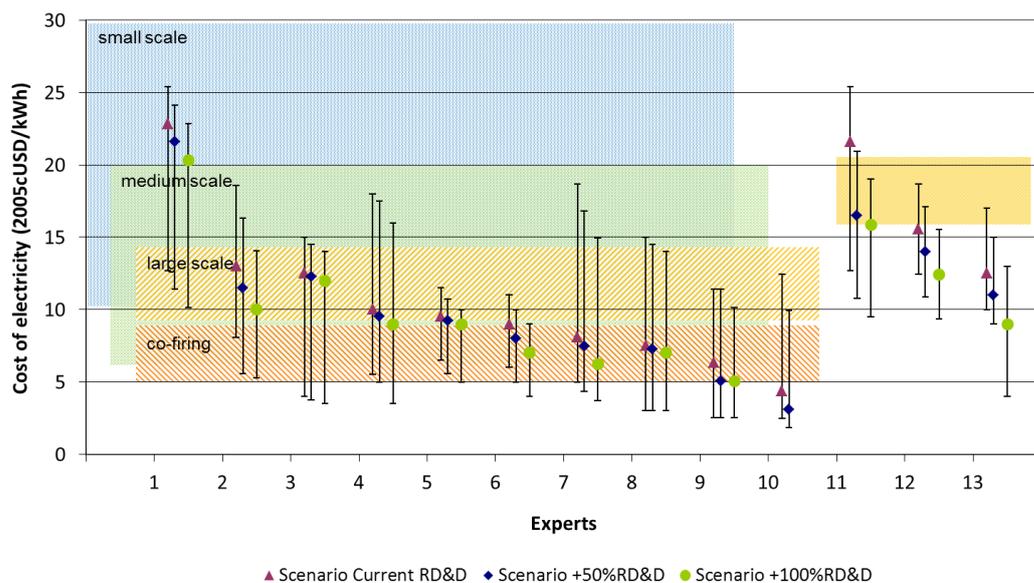


Figure 7: Estimates of the cost of electricity produced from biomass in 2030 under the BAU, +50% and +100% Scenarios. The shaded areas on the left represent the 2030 expected cost range for a mix of electricity generating technologies at different plant scale (the largest area includes the costs of small scale technologies, the medium size area covers the costs of medium scale technologies, while the two smallest areas indicate the costs of large scale and co-firing technologies) (IEA, 2012a). The shaded area on the right represents the current cost of electricity from the biochemical route (Chum et al., 2011).

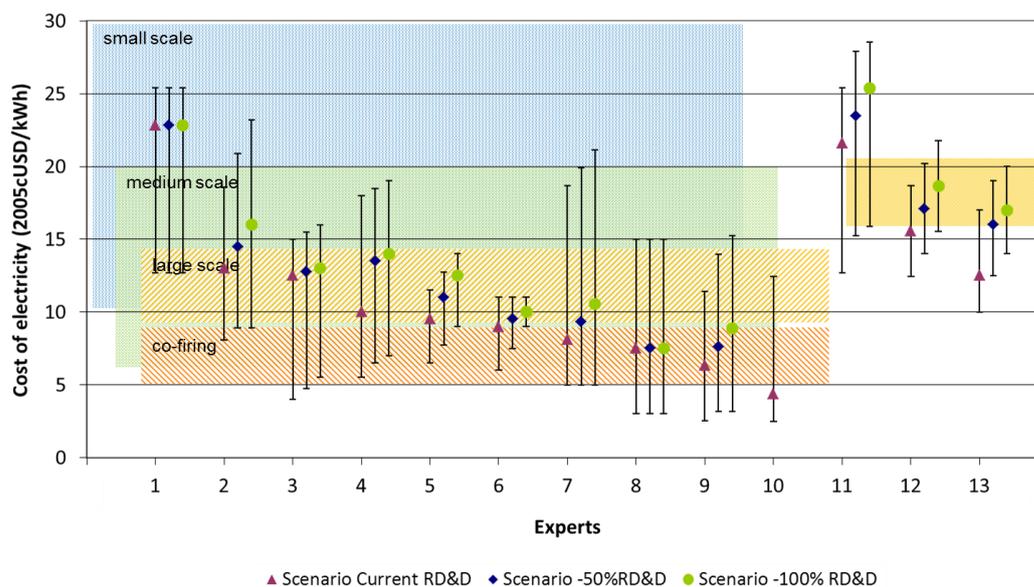


Figure 8: Estimates of the cost of electricity produced from biomass in 2030 under the BAU, -50% and -100% Scenarios. The shaded areas on the left represent the 2030 expected cost range for a mix of electricity generating technologies at different plant scale (the largest area includes the costs of small scale technologies, the medium size area covers the costs of medium scale technologies, while the two smallest areas indicate the costs of large scale and

co-firing technologies) (IEA, 2012a). The shaded area on the right represents the current cost of electricity from the biochemical route (Chum et al., 2011).

When assessing cost estimates in the reduced RD&D budget scenarios, the two groups behave in a similar way. Specifically, if RD&D funding were 50% lower or set to zero, the cost of electricity would increase by 13% and 23% according to the more optimistic experts (Experts from 2 to 10 in Figure 8), respectively. For the more pessimistic group, average costs are expected to increase by 16% and 25% in the -50% and zero RD&D scenarios, respectively. Details on the impact of RD&D funding on costs for each expert are provided in Table 5.

Table 5: Costs of electricity from biomass (cUSD/kWh) in 2030 under the current RD&D scenario, expected cost reductions under a 50% and a 100% increase in RD&D funding and expected cost increases under a -50% and a -100% decrease in RD&D funding

	Technology	BAU scenario 50 th percentile	% reduction (wrt BAU scenario 50 th percentile)		% increase (wrt BAU scenario 50 th percentile)	
			Scenario 50%	Scenario 100%	Scenario -50%	Scenario -100%
Exp 1	mix	22.85	6%	11%	0%	0%
Exp 2	mix	13	12%	23%	-12%	-23%
Exp 3	mix	12.5	2%	4%	-2%	-4%
Exp 4	mix	10	5%	10%	-35%	-40%
Exp 5	mix	9.5	3%	5%	-16%	-32%
Exp 6	mix	9	11%	22%	-6%	-11%
Exp 7	mix	8.08	8%	23%	-15%	-31%
Exp 8	mix	7.5	3%	7%	0%	0%
Exp 9	mix	6.35	20%	20%	-20%	-40%
Exp 10	cogen	4.35	29%			
Exp 11	biochem	21.58	24%	26%	-9%	-18%
Exp 12	biochem	15.54	10%	20%	-10%	-20%
Exp 13	biochem	12.5	12%	28%	-28%	-36%

Comparing our results with previous literature, the estimates of those experts considering a mix of technologies (Experts 2-9) are generally within the 2030 cost ranges provided by the IEA (2012a) for co-firing (with large scale plants and the lower part of medium scale conversion plants). The IEA range is represented by the shaded areas in Figure 7 and Figure 8). These experts generally referred to more costly technologies (such as conversions in small scale plants) to set the 90th percentile and to less costly technologies (such as co-firing) to set the 10th percentile.

Most of the cost estimates provided by the experts are close to the lower bound of the IEA projections (IEA, 2012a). When asked to assume an increase in RD&D budget (Figure 7), nine experts provided costs below the more optimistic IEA projections for co-firing²⁰.

No projection of electricity cost from biochemical conversions is available in the literature to the best of our knowledge. We therefore compare the experts' estimates to the current costs reported in the IPCC SRREN report (Chum et al., 2011). Our experts' best guesses of the 2030 costs of electricity from biomass are generally lower than the current costs provided by the IPCC, which are in the range of 17-21 cUSD/kWh. This testified to the experts' belief that RD&D investment will help improve the efficiency of these technologies (Figure 7). If RD&D support to biomass is reduced or eliminated, experts' estimates increase and become as high as the current costs provided by the IPCC (Figure 8). This implicitly indicates that reductions in the public RD&D budget would effectively translate in no cost improvement for those technologies over the next 20 years.

²⁰ Some experts remained always relatively optimistic, even in presence of a decrease in RD&D investments (e.g. Experts 8 and 9 in Figure 8)

Experts agree that feedstocks' cost is the biggest component of the final cost of electricity. However, other factors also play a role, such as the need to secure capital investment for plant construction, which varies according to the conversion technology, or the availability of heat sinks to exploit the co-produced heat.

According to the majority of the experts, the production of electricity from biomass will evolve towards a mixed system of small and large scale conversion plants. Three experts however disagree, and believe that the greater role will be played by small scale plants. Only one expert expects large scale plants to prevail.

When asked to estimate future costs in any RD&D scenario different from the current one, the uncertainty associated with the experts' estimates, and measured as the difference between the 90th and 10th percentile, increases. In particular, all but one estimate, provided for the +50% and +100% RD&D scenarios, display an average increase in the uncertainty of 5% and 7%, respectively. For the -50% and -100% scenarios, the uncertainty in the experts' estimates increases on average by 1% and 4%, respectively.

The consistency of the experts' cost estimates was checked by comparing the elicited values with the experts' probabilities that the cost of bioenergy in 2030 will be lower than threshold values, under all the different RD&D investment scenarios. About 25% of the elicited probabilities presented some inconsistencies compared to the cost predictions provided by the experts under the three funding scenarios. Follow-up interviews were therefore carried out to allow the experts to critically reassess their answers. These new updated values were those used for the analyses of the present section.

6 Diffusion of bioenergy technologies

In the fourth section of the questionnaire, we asked the experts to indicate in which geographical area of the world biomass technologies have the highest probability of reaching commercial success first. Fourteen experts declared that the European Union would reach cost competitiveness first. Brazil, the USA and China follow, and were chosen by 4 experts, 3 experts and 1 expert, respectively.

We also inquired about the dynamics of technology transfer between countries and regions of the world and their impact on national RD&D programs. Most experts (13) affirmed that the current conditions reflect a relatively successful cooperation among different countries, which results in significant knowledge spillovers. In this framework, RD&D programs not only have the purpose of developing biomass technologies nationally, but also of maintaining and improving a country's absorptive capacity. A national RD&D program is therefore a binding need to be ready to adopt breakthrough technologies developed by other countries.

Given the dynamics of technology diffusion and spillovers, we asked the experts to assess the likelihood of different biomass energy penetration scenarios by 2050. Assuming that bioenergy technologies would be technically ready to compete with conventional electricity sources by 2030, we proposed three rates of bioenergy penetration in the electricity generation mix, namely a low (10%-25%), medium (25%-50%) or high (>50%) scenario. We separately assessed these probabilities for three groups of countries where the deployment of biomass for power production could follow very different pathways: OECD, fast-growing countries and developing countries.

Table 6 shows that our pool of experts is confident in the potential of biomass technologies for electricity supply. For OECD countries, seven experts assigned a high probability (more than 60%) to the low penetration rate scenario. A bigger group believed that the medium penetration scenario is the most likely (probability higher than 70%). Altogether, these results imply that the medium penetration rate is the most likely scenario in the OECD, while the high penetration rate scenario is very unlikely to happen. These projections are more positive than those implied by the current EU legislation for the development of renewable energy technologies, which indicate that biomass will account for 9.4% of total EU final energy consumption (Beurskens et al., 2011).

Table 6: Probability of low (10%-25%), medium (25%-50%) or high (>50%) scenarios of bioenergy penetration in the electricity generation mix in 2050 in OECD, Fast-Growing and Developing countries, respectively.

	OECD			Fast-Growing			Developing countries		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Exp 1	0	80	20	20	70	10	40	60	0
Exp 2	60	30	10	80	15	5	50	40	10
Exp 3	70	20	10	80	10	10	60	30	10
Exp 4	0	70	30	0	70	30	25	60	15
Exp 5	95	5	0	95	5	0	95	5	0
Exp 6	100	0	0	100	0	0	100	0	0
Exp 7	30	70	0	30	70	0	30	70	0
Exp 8	60	35	5	50	40	10	60	30	10
Exp 9	20	70	10	20	70	10	10	80	10
Exp 10	80	20	0	100	0	0	100	0	0
Exp 11	60	30	10	50	45	5	85	10	5
Exp 12	40	50	10	60	35	5	70	25	5
Exp 13	10	85	5	10	80	10	0	70	30
Exp 14	50	50	0	30	70	0	30	70	0
Exp 15	10	80	10	10	80	10	30	60	10
Exp 16	30	70	0	50	50	0	80	20	0
Avg	45	48	8	49	44	7	54	39	7

Similar patterns emerge for fast-growing and for developing countries, thus indicating that low and even medium penetration rates are likely, while the high penetration scenario is very unlikely.

We also asked what could be the ceiling to the future share of electricity produced from bioenergy technologies. On average, a 28% ceiling was indicated, but with very high variations among the experts, who indicated figures such as 5% (1 expert), 15-30% (6 experts), 30-40% (7 experts), 50-60% (2 experts). Reasons behind this ceiling can be attributed to three main factors: limitations in feedstock availability; the development of other technologies (such as other renewable sources and nuclear) which will contribute to the generation mix; the competing uses of biomass feedstock for the production of heat, liquid fuels or chemicals.

However, the diffusion of biomass technologies is hindered by a set of potential barriers which will need to be addressed in order to support market penetration in a sustainable way. Figure 9 shows all the barriers that were identified and discussed with the experts and provides a ranking of their importance together with the suggested solution. Almost all experts expressed concern about the sustainability of biomass supply. Competition for land with food crops and with carbon sinks (e.g., forests and grasslands), the extensive use of water, the pollution deriving from the use of fertilizer and the threats to biodiversity and soil productivity are the major concern linked with biomass technologies diffusion.

Eight experts also affirmed that most of these issues and externalities can be mitigated with adequate policies, such as a certification system (as already existing for liquid fuels in the EU) that guarantees the sustainability of resources and that controls the origin of feedstocks. Three experts suggested that the choice of feedstock (i.e. use of residual

biomass and wastes in place of energy crops) is crucial with respect to the sustainability of biomass supply.

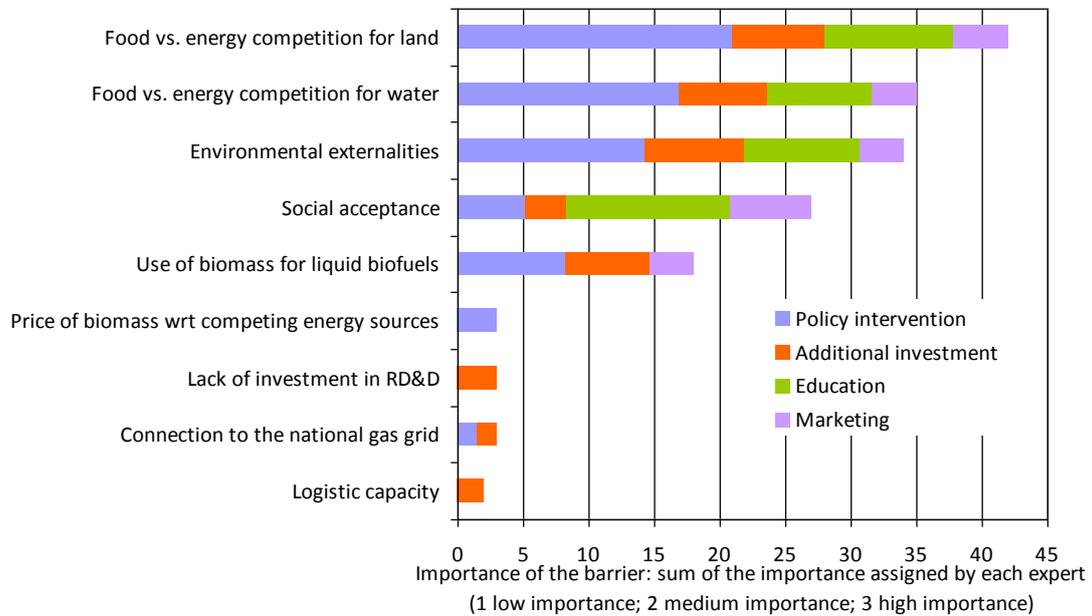


Figure 9: Factors which could represent non-technical barriers to the diffusion of bioenergy technologies and potential solutions to overcome the barriers.

According to all experts, life cycle emissions of GHG for electricity from biomass are low, provided that the feedstocks are produced and delivered sustainably. This can be promoted, as previously pointed out, by a certification system of biomass supply. However, since emissions can vary with the specific application and with the location of the project, life cycle emissions should always be assessed for the specific bioenergy system, as specifically pointed out by five experts. Computing life-cycle emissions by considering the whole supply chain in specific regions and applications would allow accounting for all sources not only for direct but also for indirect emissions, such as those due to the use of fertilizers and pesticides or of digestate in anaerobic digestion processes, as well as methane emissions from the use of biogas in engines.

Furthermore, two experts highlighted the necessity of investing to improve agricultural development. Bioenergy production in the public eye is often associated with the presence of waste plants; for this reason, social acceptance of bioenergy is another major non-technical barrier that should be overcome with education and marketing. Finally, barriers related to economic and finance issues were considered less relevant than those related to environmental and sustainability issues.

7 Conclusions

Bioenergy is a crucial component of the EU renewable energy targets. However, progress is needed to guarantee sustainable feedstocks supply, to improve the energy conversion and to make bioenergy competitive with fossil fuel electricity.

We study the future prospects of bioenergy technologies relying on sixteen EU leading experts through an *ad hoc* elicitation protocol. We assess the current status of technologies, their future developments and the expected cost of electricity from biomass conditional on different EU public RD&D funding scenarios. This results in important insights and policy recommendations for bioenergy.

Many of the selected technologies, which are currently under development, present a good potential to overcome technical bottlenecks by 2030. However it is very unlikely that electricity from biomass will be cost-competitive with electricity from fossil fuels in the absence of a climate policy. Several technologies, such as gasification, are already in the demonstration phase. RD&D is thus crucial in supporting the final phases of the development of bioenergy technology, and investments should be concentrated on applied research and demonstration. On the other hand, basic research should always be present although with a less relevant role. This is in line with current guidelines for the

development of bioenergy technology (e.g., European Bioenergy Industrial Initiative) but in sharp contrast with the EU historical budget allocation, mainly focused on basic research.

Assuming the current level of annual EU public RD&D until 2030, most experts' best estimates of the cost of electricity from biomass lie in the 7.5-13 cUSD/kWh range for a mix of technologies, with a 2030 average cost of 8.9 cUSD/kWh.²¹ The cost of electricity from biochemical conversions is higher, on average estimated at 16.5 cUSD/kWh. Without any variation in RD&D in the next 20 years, the lower cost scenario (3 cUSD/kWh) is unlikely.²² The probability that electricity from biomass will be competitive with electricity from fossil fuels (5.55 cUSD/kWh) is equal to 21%. On the other hand, with a climate policy in place (cost of electricity from coal at 11.26 cUSD/kWh), the probability rises to 54%, making cost competitiveness in 2030 more likely than not.

Increases in RD&D funding lead to a decrease of the cost of electricity from biomass, which differs depending on the conversion route considered. For thermochemical conversions, a 50% increase in RD&D leads to an 8% reduction of costs (9.5 cUSD/kWh). For this technology, further increases of the RD&D effort are unlikely to have a significant effect on cost reduction; however, they reduce the divergence of experts' estimates of the future costs of electricity.

The role of RD&D investment for biochemical conversions is rather different. The average expected cost decreases by 16% and 25% with 50% and 100% more RD&D

²¹ The average cost excludes Expert 1, see Section 5 for details.

²² We use here the same framework for the treatment of uncertainties as defined in the IPCC AR4 report (IPCC, 2007): "Where uncertainty in specific outcomes is assessed using expert judgment and statistical analysis of a body of evidence (e.g. observations or model results), then the following likelihood ranges are used to express the assessed probability of occurrence: virtually certain >99%; extremely likely >95%; very likely >90%; likely >66%; more likely than not > 50%; about as likely as not 33% to 66%; unlikely <33%; very unlikely <10%; extremely unlikely <5%; exceptionally unlikely <1%."

funding, respectively. However, the cost of electricity generated with these technologies remains consistently higher than that obtained through thermochemical conversions. For both conversion routes, even when doubling the RD&D effort, it remains unlikely (33% probability) that electricity from biomass will be competitive with that from fossil fuels without carbon policy. On the other hand, if a carbon policy were in place, the cost-competitiveness would likely be reached (69% probability).

The role of RD&D on electricity costs is confirmed by the results relative to the lower-than-current RD&D scenarios. An RD&D reduction by half or more would make the cost competitiveness of electricity from biomass without carbon policy very unlikely (9% probability). With a carbon policy in place, chances would be higher (40% probability), but still lower than in the scenarios assuming an RD&D program.

The EU emerged as the region of the world with the greatest probability of reaching a breakthrough and thus making electricity from biomass competitive. The chances of this happening in Brazil or in the USA are significantly smaller. This probably reflects the different focus of EU and non-EU policy: the former more focused towards the promotion of biomass for electricity supply, the latter more focused on biofuel technologies.

Experts showed little consensus when asked to assess the future contribution of bioenergy to the production of electricity, even though they agreed in considering very unlikely a high penetration scenario. Half of the experts foresee a possible 10-25% penetration scenario in 2050, while the others seven experts evaluate a 25-50% diffusion scenario as the most likely to happen. This vision is analogous for OECD, fast growing and developing countries; however a lower penetration rate appears more probable for the latter group. The scarcity of feedstocks and the competing use of

biomass for bioenergy and biofuels emerged as the two most important factors limiting the diffusion of electricity from biomass.

Experts expressed concern regarding the sustainability of biomass supply and the consequences that an increasing use of biomass could have on global land use, biodiversity and water use. However, these issues can be managed and negative impacts can be limited when policies that promote biomass sustainable use (such as certification schemes) are put in place.

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