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Transitions in biofuel technologies: An appraisal of the social impacts of cellulosic ethanol using the Delphi method

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A B S T R A C T

The sustainability of biofuels produced from food crops has become a focus of public and scientific scrutiny in the past few years. In the case of ethanol production, advanced technologies aim at avoiding controversy by using instead cellulosic biomass contained in wastes, residues and dedicated energy crops. However, despite the positive expectations that drive the development of the so-called "cellulosic" ethanol, sustainability challenges remain to be elucidated. Expecting to contribute to closing the gap in the field of the social assessment of biofuels, this paper reports and analyses the results of a Delphi survey that explored the perception of biofuel experts from different countries on potential social impacts of cellulosic ethanol. The complexity of appraising impacts emerges as one important conclusion of the study along with the realisation that these will be context-specific. Except for the case of municipal solid waste used as feedstock, such a technological transition might not be able to ameliorate the issues already faced by conventional ethanol, especially when production is based in poorer countries. This is because impacts of cellulosic ethanol depend upon both the technical dimension of its production and the socio-political context of locations where production might take place.

1. Introduction

Alongside the development of a promising international market, in the last decade liquid biofuels have been promoted as strong candidates in the search for alternatives to the use of fossil fuels in the transportation sector. However, the brisk development of a global commodity chain of liquid biofuels (Raikes et al., 2000) did not come without its share of controversy, as it has been facing great challenges regarding the governance of its impacts. In the development of biofuels, two antagonistic narratives have prevailed. On the one hand biofuels have been framed as an important, strategic solution to reduce greenhouse gas (GHG) emissions while increasing the energy security of countries that are dependent on oil imports. On the other hand however, some biofuel production chains have been coupled to both direct and indirect land-use changes, leading to increasing GHG emissions and putting pressure on food security. Because of the high levels of uncertainty regarding its potential impacts and already proven detrimental effects on the environment and society, large-scale production of liquid biofuels has become a focus of public and scientific scrutiny (see, for example, Doornbosch and Steenblik, 2007; Scharlemann and Laurance, 2008; Ajanovic, 2011; Selfa et al., 2011; Wright and Reid, 2011). As a response to the latter, the European Union and governments around the world have been supporting innovations in biofuel technologies, such as the ones involved in the conversion of non-edible biomass into liquid biofuels (EC, 2013). These particularly aim at addressing issues of technical efficiency and the environmental and social sustainability of biofuels by

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achieving greater reductions in GHG emissions while avoiding negative impacts on food security along their lifecycle.

Ethanol is the world's most produced type of liquid biofuel. The United States and Brazil dominate production, but use in Europe is also increasing (RFA, 2012). Technological innovations in ethanol production are focused on bringing "second-generation" biofuels to market. These 'advanced biofuels'[1] commonly make use of the cellulosic components of biomass, which may be obtained from forestry and agricultural residues, municipal solid waste (MSW) and dedicated energy crops, such as grasses and short rotation coppice (SRC). The so-called cellulosic ethanol is commonly considered to offer advantages in comparison to conventional, "first-generation" ethanol made from edible crops rich in sugar or starch. These advantages include further reductions in GHG emissions and reduced competition with food production (Farrell et al., 2006; Hahn-Hägerdal et al., 2006; Solomon et al., 2007; González-García et al., 2010; Viikari et al., 2012; Mabee et al., 2011; Borrion et al., 2012). Based on these benefits, several countries have been encouraging the development and economical scale-up of cellulosic ethanol.[2] Presently, this is generally limited to production at experimental and demonstration scales because of economic and technical barriers (Limayen and Ricke, 2012).

Despite the positive expectations that drive the development of cellulosic ethanol, a number of important sustainability challenges have also been highlighted. Many of these derive from consideration of the impacts of conventional ethanol (Mohr and Raman, 2013). Moreover, previous research has demonstrated that the social dimensions of ethanol impacts are largely overlooked in the scientific literature; a transition from conventional to cellulosic ethanol may entail negative social impacts, and there is a lack of research dedicated to the appraisal of potential social trade-offs of such a transition (Ribeiro, 2012, 2013a).

Following up on previous work and expecting to contribute to closing the gap in the field of the social appraisal of advanced biofuels, this paper reports and analyses the main results of a Delphi survey that explored the perception of twenty-four biofuel experts from seven countries[3] on potential social impacts of cellulosic ethanol. Impacts were assessed against different hypothetical scenarios. These were based on the type and source of raw material for the production of cellulosic ethanol in different regions from the global North and South. Experts appraised impacts with regard to their probability of occurrence and two additional criteria that are less explored in the analysis of the impacts of technological change: reversibility and monitorability. Since ethanol production may take place in different locations across the world, the main objective of the survey was to stimulate reflection around the social sustainability of ethanol under different contexts. We focus the analysis in terms of 'best' and 'worst-case scenarios' that stem from quantitative and qualitative data obtained in the mixed methods survey (Bryman, 2012). The combination of these different data sets was helpful in unveiling interesting aspects of the variables assessed and supporting the findings of each approach.

The challenge of such an appraisal emerges as one important conclusion of the study along with the realisation that the potential social benefits and drawbacks of cellulosic ethanol will be highly context-specific and complex. In addition to highlighting the difficulty of analysing complex problems, participants revealed the dual, sometimes ambiguous, technical and social nature of their 'solutions' (Quintanilla, 1993). Main findings indicate that experts are sceptical if a transition to advanced biofuel production will be able to ameliorate the issues faced by the production of conventional ethanol, especially when production is based in poorer countries of the global South. Production from MSW may however be the exception to this rule.

This paper is divided into 6 sections. It starts with an introduction to the Delphi method (Section 2), followed by a description of the survey process (Section 3). It then presents a summary of the results (Section 4) and a discussion on the limitations and strengths of the study (Section 5). Finally, it offers key considerations on the development of cellulosic ethanol (Section 6) followed by some concluding remarks (Section 7).

2. The Delphi method: some applications and critiques

The Delphi method is a forecasting technique which elicits expert knowledge from a variety of participants (Scapolo and Miles, 2006). The makeup of this expertise is determined by the design of the exercise. Developed in the 1950s in the United States as an experiment aimed at estimating bombing requirements (Dalkey and Helmer, 1963), a Delphi traditionally involves an anonymous survey using questionnaires with controlled feedback to allow iteration within a panel of experts (Linstone and Turoff, 2011). A key feature of the Delphi technique is its potential to disclose subjective value judgements of a group of individuals assessing complex problems that are characterised by varying levels of uncertainty (Linstone and Turoff, 2002). It is also understood as a tool for reaching expert consensus through scientific discourse and helping to solve complex situations in which, while scientific knowledge elements are relatively certain, the relations between variables are very complex (Bijker et al., 2009).

The Delphi method has been employed in social impact assessment (SIA) to gather public opinion through community engagement in SIA studies (Burdge and Robertson, 1990); in environmental impact assessment (EIA) to assist in the estimation of impacts (e.g. Green et al., 1990; Vizayakumar and Mohapatra, 1992) and as an instrument for the evaluation of available tools for other types of assessment (e.g. Buytaert et al., 2011). The Delphi technique has also been used as an analytical tool for structured interaction in technology assessment (TA) between experts and other relevant actors (van den Ende et al., 1998). Among other methodologies for foresight and forecasting, such as lifecycle assessment and future-oriented bibliometrics, Delphi studies can serve as tools for decision-making in the context of the development of emerging

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[1] The term 'advanced' in this work refers to a type of biofuel that is obtained from processes that involve technological innovations in comparison to conventional ones.

[2] In the United States and European Union this support is formulated in the Energy Independence and Security Act of 2007 and in Directive 2009/28/EC, respectively.

[3] Brazil, Canada, India, Spain, Sweden, UK and the US.

technologies, helping to increase reflexivity in innovation systems (Barben et al., 2008).

The choice of a specific design and the methodological characteristics of a Delphi process are dependent on the research question defined by the analyst and vary significantly among studies (Hasson and Keeney, 2011). Critiques of the method have stemmed from a plethora of analyses, focusing on different dimensions of the process and its potential drawbacks. Landeta (2005) points out several weaknesses of the method: participants' biases, bias in expert selection by the facilitators, the idea of consensus as an approximation to truth, the limitations to participants' interaction in controlled feedback, the weight of the interests of who runs the study in the design of the methodology, and the difficulty in appraising the method's accuracy and reliability are all key concerns (Landeta, 2005:469). In another evaluation of the Delphi method, Tichy (2004) addressed the issue of how different levels of expertise (or specialisation) among participants influence their levels of optimism and pessimism regarding proposed scenarios. Finally, Hussler et al. (2011) have demonstrated the importance of panel composition, arguing that non-expert and expert panels will often produce significantly different results.

However, if its pitfalls are acknowledged and methodological rigour is ensured, the Delphi method is able to produce robust long-term forecasts (Parente and Anderson-Parente, 2011), with higher levels of accuracy in its results than for those obtained from unstructured group interactions (Rowe and Wright, 1999). The method can also be combined with other forecasting techniques and social research methodologies. In technology assessment, for example, it can be used in association with analytic hierarchy process and cross-impact method, among others (Tran and Daim, 2008). A key argument in defence of the Delphi method, forwarded by some of its main theorists is that ultimately when making judgements in situations of high uncertainty, one head should be better than none and multiple heads better than one (Linstone and Turoff, 2002:234). Importantly in such situations, the method allows overlooked research topics to be raised and discussed where in other group situations they might remain hidden (Cuhls, 2003).

This section has briefly laid some applications, challenges and opportunities of the Delphi method. As indicated above, Delphi studies can be useful to help achieving many different objectives and might have different degrees of complexity. The survey presented in this paper corresponds to an exploratory exercise that aimed to elicit the perception of biofuel experts regarding potential social impacts of cellulosic ethanol. It attempts this by promoting reflection around a set of previously defined variables and against different scenarios and criteria. In contrast to other future-oriented studies, these initial scenarios were rather simple and open. Moreover, consensus was not an objective of the survey, although agreement levels are discussed in this paper. Providing with structured feedback on experts' responses in questionnaires, eliciting their knowledge on complex issues and revealing some of their assumptions in the process are therefore the main elements of the present study, and so the reasons for structuring it around the Delphi method. Section 3 describes the different aspects of the survey in more detail.

3. A Delphi study for the social appraisal of cellulosic ethanol

The Delphi study presented here was devised in a structured format in order to assess a list of pre-defined impacts drawn from previous work documented in Ribeiro (2013a). Two generic pathways were used to illustrate the main technical differences between the production of conventional and cellulosic ethanol. Participants used three criteria to appraise the potential impacts of ethanol: their probability, reversibility and monitorability. This was done against a range of different hypothetical scenarios where types of land, feedstock and geographical locations for the production of cellulosic ethanol were variables. Sub-sections 3.1 to 3.4 describe the design of the study and the development of the survey process.

3.1. The survey process

The survey was run online between April and July 2013 using the Adobe Forms Central platform. It was anonymous and divided into two rounds. After the last round we circulated an evaluation questionnaire to obtain feedback from participants regarding their impressions of the study and the method used. Selection of potential participants was based on their recognised expertise and familiarity with the topic of biofuels' sustainability. Disciplinary diversity and geographical diversity were the main criteria that guided the selection of invitees (see Table 1 and Fig. 1).

Participants were identified in the peer-reviewed literature, mainly from the references used in Ribeiro (2013a), and through the use of snowball sampling from invited experts. Out of thirty-nine invitations sent ($n = 39$), a total of twenty-four experts ($n = 24$) from seven countries took part in the first round of the survey, indicating a response rate of 61.5%. Fifteen participants ($n = 15$) remained in the study and completed the questionnaire for the second round. Despite a dropout rate of 37% between the two rounds, panellists were still representative of the geographic diversity of the first round group (Fig. 1).

3.2. Potential social impacts of cellulosic ethanol

Social impacts might involve large or small communities, groups of people or individuals. They have different dimensions, as they might refer to social change processes (e.g. an

Table 1
Main areas of expertise of participants[a].

Agricultural economics[b]
Bioenergy systems
Biofuel supply chains
Biofuel governance[b]
Corporate social responsibility[b]
Critical environmental social science
Ecosystem ecology[b]
Energy and environmental policy[b]
Energy and society
Energy planning[b]
Environmental management
Ethics
Integrated analysis of farming systems[b]
Life cycle assessment[b]
Public opinion[b]
Renewable energy[b]
Rural sociology[b]
Sociology
Sociology of technology[b]
Sustainability certification[b]

[a] Areas are “biofuel-related”, inserted by participants as free text.
[b] Areas represented in both rounds.

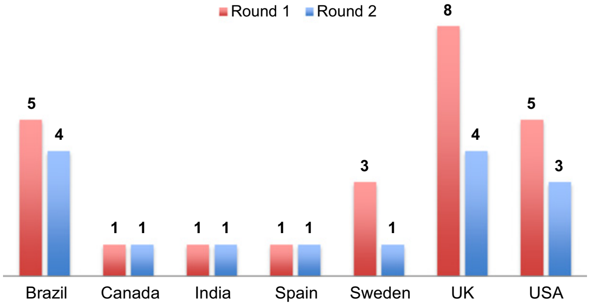

Fig. 1. Number and geographical location of participants.

increase in human exposure to toxic substances or an increase in wages) or to the human experience related to change (i.e. the actual physical or psychological effects of the change as perceived by people and their response to the experience). Although these dimensions are neither definitive nor linear, they can be useful to understand that social change processes and social responses to change often create subsequent social changes, making it impossible to determine and define all the levels of a social impact (Van Schooten et al., 2003; Vanclay, 2002). Therefore, the depth to which a social impact is described depends on the decisions made by the analyst or other actors that take part in the assessment. Distinguishing between social change processes and the human experience related to change can be helpful as it calls attention to the fact that, while social change processes might be generalizable, the human experience and responses or adaptation to change will likely differ among actors and in different contexts.

Eight potential impacts involved in a transition from the production of conventional to cellulosic ethanol were drawn from Ribeiro (2013a). This study developed a comprehensive matrix of social aspects of ethanol used as a support tool for a systematic review of the peer-reviewed literature on the topic. The identification and definition of impacts aimed to generalise a number of social change processes that would be relevant in the transition between two technological pathways for conventional and cellulosic ethanol. These are described in Section 3.3. The main technical changes of such a transition are related to the type of feedstock or raw material used for ethanol production and the processes to convert that feedstock into ethanol. Variables were derived from these impacts and were framed to focus on changes at two different stages of the lifecycle of ethanol: feedstock production (I) and conversion processes at the refinery (II) (Table 2).

3.3. Technological transitions in ethanol production

A variety of technological pathways exist for ethanol production. In the case of cellulosic ethanol, feedstock pretreatments and conversion routes can be multiple and complex, involving different combinations of biological, chemical and physical processes (Sanchez and Cardona, 2008; Kumar et al., 2009; Menon and Rao, 2012). In order to guarantee the feasibility of a survey that addresses a complex technical system, two generic technological pathways (TP1 and TP2) were devised to inform the analysis of the technical aspects of a transition between conventional and cellulosic ethanol (Fig. 2). These technological pathways were designed to represent hypothetical real-world scenarios, based on current technical literature.

In TP1, conventional ethanol is produced from starchy or sugar crops, such as maize, wheat, sugarcane and sugar beet. Feedstock for TP2 is lignocellulosic material such as woody residues and agricultural residues like corn stover, wheat straw and sugarcane bagasse, dedicated energy crops like switchgrass and SRC and the organic fraction of SMW, which would otherwise be destined to landfills (Naik et al., 2010; Sims et al., 2010). In TP2, these are converted into cellulosic ethanol. The main technical differences between TP1 and TP2 relate to the access to sugar molecules for fermentation and the types of molecules that are fermented into ethanol. Both factors depend on the characteristics of the feedstock or raw material used, i.e. the source of sugar. While in starchy and sweet crops (as in TP1) sugar molecules are more readily accessible and easier to ferment, lignocellulosic material (as in TP2) presents a lignin barrier that hinders the access to cellulose and hemicellulose, complex polymers made of glucose and other types of sugars that are more difficult to ferment into ethanol (Sun and Cheng, 2002).

3.4. Criteria and scenarios for appraisal of social impacts

Three criteria were chosen to explore different dimensions of potential social impacts of cellulosic ethanol: their probability of occurrence, their degree of reversibility (dependent, for example, on the geographical scale of an impact and the potential costs to mitigate it) and their degree of monitorability, i.e. the possibility of identifying and measuring an impact so that mitigation strategies can be put in place (dependent, for example, on the complexity and number of indicators needed, levels of pre-existing knowledge and amount of resources needed). Although subject to different interpretations, 'probability' is a common dimension of the analysis of technological change in future-oriented research (Loveridge and Saritas, 2012). 'Reversibility' and 'monitorability' are less popular criteria in the field of technology and social change analyses, but were deemed as worth of exploring due to their role in related fields of research. The notion of reversibility is attributed to interpretations of the Precautionary Principle, and is articulated in frameworks for ecological and sustainability analysis at both policy and project levels (Dovers, 1995; Matheson et al., 1997; Faruk et al., 2002). It has also been directly explored in environmental analysis of the impacts of biodiesel production

Table 2
Definition of potential social impacts.

Variable #	Stage	Definition
1	I	Inclusion of small-scale farmers in the supply chain of cellulosic ethanol, which may be affected by different farming techniques and management needs (e.g. farm inputs, machinery, logistics etc.).
2	I	On-site food security, defined as the current and future equitable and sufficient access to affordable nutritious food by locals, especially vulnerable groups. It may be affected by the competition for land and other natural resources (on-site ecosystem services) between cellulosic feedstock and food crops, and by impacts of the former on soil fertility.
3	I	Off-site food security, defined as the current and future equitable and sufficient access to affordable nutritious food by people, especially vulnerable groups. It may be affected by direct competition (e.g. replacement of food crops plantations by cellulosic feedstock) or indirect competition (e.g. displacement of livestock production in land that could be used for food production in the future) for land and other natural resources of cellulosic feedstock and food crops, and by impacts of the former on soil fertility.
4	I	Water security (feedstock-related), defined as the current and future equitable and sufficient access to clean (safe) water by people, especially vulnerable groups. It may be affected by changes in the intensity of water use for feedstock irrigation and by water pollution (e.g. contamination by chemical inputs released in the fields).
5	I	Biodiversity security, defined as the preservation of plant and animal species that are valuable to human societies (e.g. for biological pest control, for traditional uses, or to maintain the flow of other ecosystem services). It may be affected by, e.g., the implementation of monocultures, introduction of invasive plant species or deforestation.
6	II	Employment generation for low-skilled or unskilled workers at the power plant (conversion processes) and other facilities (R&D) due to changes in the demand for workers with lower professional qualification.
7	II	Inclusion of small-scale producers, i.e. locally owned and run facilities in the supply chain of cellulosic regarding the access (availability and affordability) to bioconversion technologies, e.g. machinery and industrial equipment, enzymes, chemical and energy inputs etc.
8	II	Water security (related to conversion processes needs), defined as the current and future equitable and sufficient access to clean (safe) water by people, especially vulnerable groups. It may be affected by changes in the intensity of water use in the overall conversion process (e.g. hydrolysis and fermentation) and by water pollution.

(Kaercher et al., 2013) and identified as an important, but overlooked dimension of impact significance in environmental impact assessment practice (Lawrence, 1997). Verbruggen (2013) offers a comprehensive review on the usage of the concept by different disciplines in search of a workable definition for policy-making purposes. In attempting to bridge the gap between the use of reversibility and irreversibility in the natural and social sciences, the author proposes a generic definition of reversibility as “the ability to maintain and to restore the functional performance of a system” (Verbruggen, 2013:26). Finally, the task of monitoring social change processes in the assessment of policies, programmes, plans or projects has been largely acknowledged in the social impact assessment literature as a crucial component of the assessment process (Becker, 2001; Vanclay, 2003; Baines et al., 2012; Esteves et al., 2012)

Questionnaires used in the two rounds included close-ended questions for the appraisal of the probability, reversibility and monitorability of each of the eight impacts against different scenarios, with a space for comments at the end of each section. In round 1, five generic scenarios (A–E) based on the type of feedstock and the type of land for the production of cellulosic ethanol guided the appraisal of impacts related to the stage of feedstock production (Fig. 3). For the stage of conversion processes, scenarios were differentiated in terms of low, middle and high-income countries. Initial scenarios were informed by Ribeiro (2012, 2013a). Close-ended questions consisted of five point Likert-type items, a variation of the Likert scale that is based on the analysis of individual items rather than on the analysis of the summed item scores (Clason and Dormody, 1994).

After completing the first round of the survey, participants received a report on its quantitative and qualitative results, which informed the questionnaire devised for round 2. In round 2, the same criteria were used to explore the same set of impacts of the first round. However, building on the results of the latter, the initial five generic scenarios (used in round 1) were further divided into more specific, hypothetical sub-scenarios regarding different geographical locations and more specific feedstocks (Table 3).

4. Results of the Delphi survey

Quantitative and qualitative analysis of the results were performed. In this paper, discussion of the former is based on participants' ratings of variables in the second round (median and interquartile range values). Since the questionnaire used in the second round involved different scenarios compared to the first one, no statistically significant correlation was expected between results of different rounds. However, qualitative data, in the form of comments, was collated and coded for both rounds and are also summarised alongside quantitative results in the next sections of this paper. Bryman (2012) argues that although there are epistemological and ontological differences between quantitative and qualitative research, their dichotomies, e.g. empiricist versus constructivist approaches, numbers versus words etc. are often exaggerated. In other words, their analyses should not be regarded as incommensurable. As the questionnaires designed for the present Delphi included both quantitative and qualitative components, the study is characterised as a mixed methods exercise (Bryman, 2012).

4.1. Inclusion of small-scale farmers in the supply chain of cellulosic ethanol

The inclusion of small-scale farmers as suppliers of raw material in the supply chain of cellulosic ethanol may be affected by various factors, such as costs of adaptation to different farming techniques, technologies and management needs, farmers' perception of investment risk and the existence of support mechanisms offered by governments. For the majority of scenarios, experts considered that the inclusion of small-scale farmers in the supply chain of cellulosic ethanol would be rather unlikely (Table 4). An exception to this might be

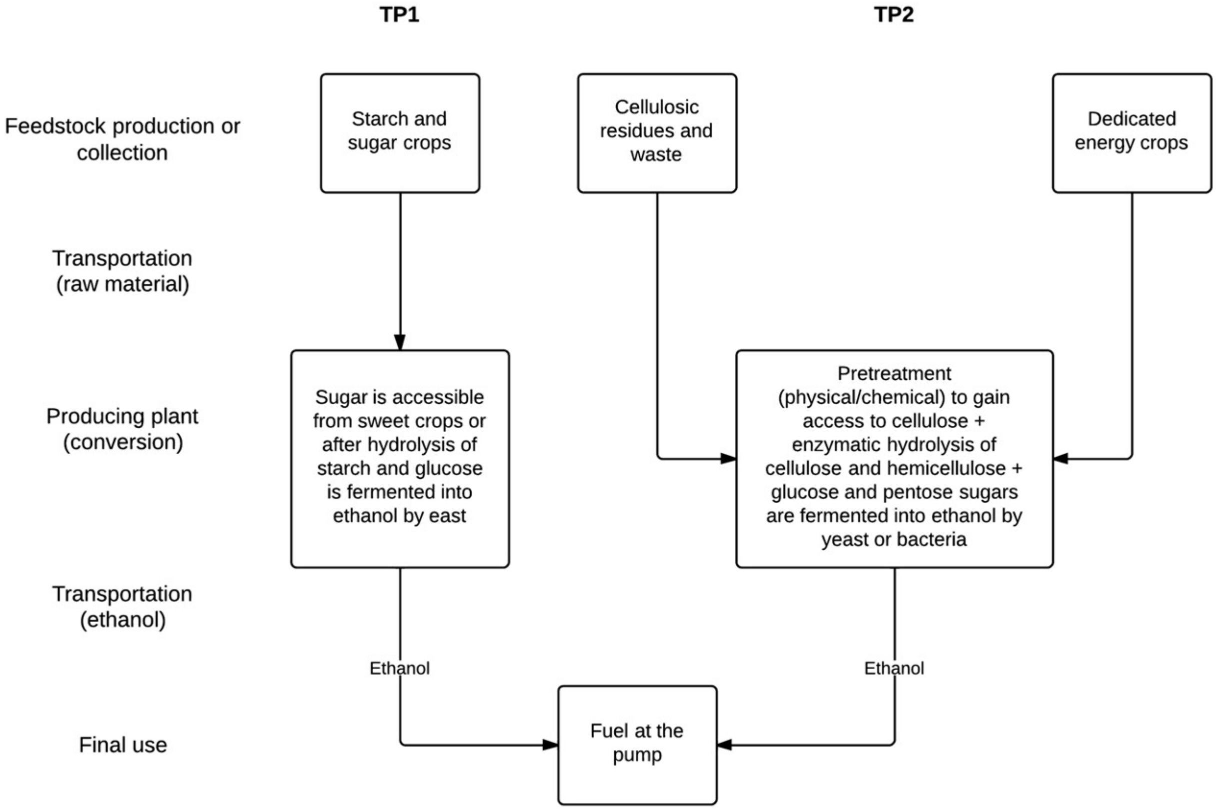

Fig. 2. Technological pathways for first-generation (TP1) and cellulosic ethanol (TP2) production.

situations where cellulosic ethanol is produced from residues, (e.g. wheat straw), from land dedicated to agricultural or forestry activities independent of biofuel production in countries such as the UK or Germany. This would be the best-case scenario for small-scale farmers. Conversely, the probability that small-scale farmers would be successfully included in production chains in poorer countries was suggested to be low, irrespective of feedstock.

Panellists indicated that the collection of residues could be costly due to high technological costs and the requirement of qualified labour. Its economic feasibility was also perceived to be dependent on the geographical distribution of ethanol plants (i.e. how close and well-connected these are to locations where the raw material is produced). Another point made by participants is that there is a risk that only large-scale producers would be able to provide great levels of feedstock at lower prices as demanded by the ethanol industry. As pointed out by one individual, "there are almost no small (i.e. peasant) farmers involved in bioenergy feedstock production in the US, although there are efforts to involve non-corporate farmers and

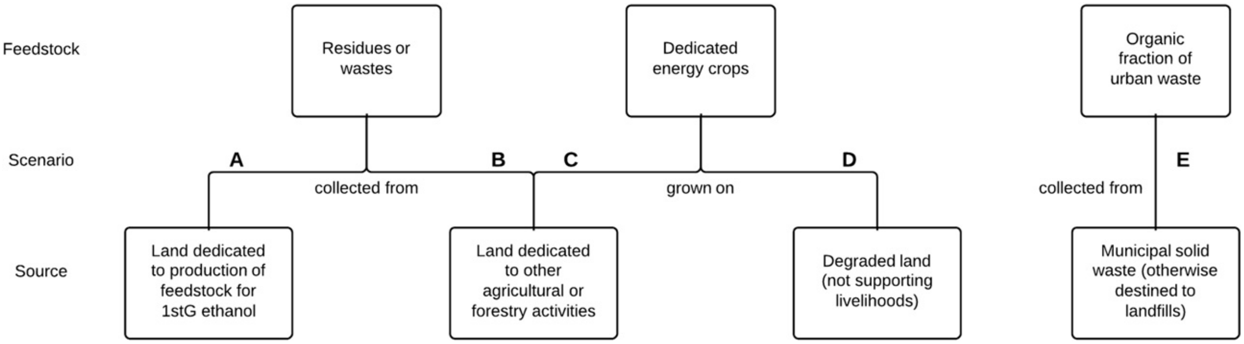

Fig. 3. Overview of feedstock-related scenarios for cellulosic ethanol.

Table 3
Scenarios (round 1) and sub-scenarios (round 2).

Scenario A	
Feedstock: Residues or wastes	
Source: Land dedicated to production of feedstock for 1G ethanol	
A1	**A2**
Region: Centre-South of Brazil	**Region:** Eastern Africa (e.g. Sudan, Tanzania, Kenya)
Type of feedstock: Sugarcane bagasse, straw, leaves	**Type of feedstock:** Sugarcane bagasse, straw, leaves
Scenario B	
Feedstock: Residues or wastes	
Source: Land dedicated to other agricultural or forestry activities	
B1	**B2**
Region: Western Europe (e.g. UK, Germany)	**Region:** South Asia (e.g. India)
Type of feedstock: Wheat straw	**Type of feedstock:** Rice straw
Scenario C	
Feedstock: Dedicated energy crops	
Source: Land dedicated to other agricultural or forestry activities	
C1	**C2**
Region: United States	**Region:** Eastern Africa (e.g. Uganda)
Type of feedstock: Short rotation coppices (e.g. Poplar)	**Type of feedstock:** Short rotation coppices (e.g. Eucalyptus)
Scenario D	
Feedstock: Dedicated energy crops	
Source: Degraded land (land disturbed by human impact)	
D1	**D2**
Region: Eastern Europe (e.g. Poland, Hungary)	**Region:** Western Africa (e.g. Benin, Togo)
Type of feedstock: Pernnial grasses (e.g. Miscanthus, switchgrass)	**Type of feedstock:** Perennial grasses (e.g. Miscanthus, switchgrass)
Scenario E	
Feedstock: Organic fraction of urban waste	
Source: Municipal solid waste (otherwise destined to landfills)	
E1	**E2**
Region: Canada	**Region:** Eastern China (e.g. Shangai)
Type of feedstock: Urban waste	**Type of feedstock:** Urban waste

Table 4
Inclusion of small-scale farmers in the supply chain of cellulosic ethanol.

Scenario	Probability			Reversibility		
	(1 — lower "very unlikely", 5 — higher "very likely")			(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N	Median	IQR	N
A1	2.00	0.75	14	3.00	2.00	14
A2	2.00	1.00	13	3.00	2.00	13
B1	4.00	2.00	13	3.00	1.00	12
B2	2.50	2.00	12	3.00	2.00	12
C1	2.50	2.00	14	2.50	1.00	14
C2	2.00	1.00	12	2.00	0.00	14
D1	3.00	2.00	14	3.00	1.00	14
D2	2.50	1.00	10	2.50	1.00	14

	Monitorability		
	(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N
Low-income countries	2.00	1.75	14
Middle-income countries	3.00	1.00	14
High-income countries	4.00	1.00	15

private landowners in growing dedicated energy crops on abandoned agricultural land" (participant 22). Moreover, according to another panellist, the 'lobby power' held by large landholders might also have a detrimental effect on the inclusion of smallholders in the ethanol supply chain.

Should small-scale farmers begin to grow dedicated energy crops for the production of cellulosic ethanol, they would be likely to face difficulties in returning to their previous cropping systems (Table 4). Important factors that need to be considered in this regard are costs and return on investment, the type of crop being cultivated and the related process of land-use change. An example is the case of perennially rooted crops, which are perceived as being "harder to dislodge than, for example, fodder maize" (participant 15). Experts argued that this was not simply a situation of 'ploughing up the crop'; reversibility needs to include business considerations, such as investment risk and the development of complex, new markets around products and co-products, which significantly complicate the picture.

In the opinion of participants, monitoring the inclusion of small-scale farmers in the supply chain of cellulosic ethanol would be more difficult in poorer countries because of a lack of resources and potentially corruptive practices (Table 4). Despite this, there may be ways of implementing invoice systems to track the origin of the feedstock and controlling financial transactions or lorry loads to monitor the activities of farmers.

Table 5
Negative impacts on food security.

Scenario	Probability						Reversibility					
	(1 — lower "very unlikely", 5 — "very likely")						(1 — lower "very difficult", 5 — higher "very easy")					
	On-site food security			Off-site food security			On-site food security			Off-site food security		
	Median	IQR	N	Median	IQR	N	Median	IQR	N	Median	IQR	N
A1	3.00	1.50	15	2.50	1.75	14	4.00	1.00	13	3.50	2.00	14
A2	3.00	1.50	14	3.00	2.00	14	3.00	1.00	13	4.00	2.00	13
B1	2.00	1.00	15	2.00	1.00	14	4.00	0.00	13	4.00	1.00	14
B2	3.00	1.00	13	2.50	1.00	12	3.00	1.00	13	4.00	1.00	13
C1	2.00	1.00	15	3.00	0.75	14	3.00	1.00	12	3.00	1.00	13
C2	4.00	1.00	14	3.00	1.50	14	2.50	1.00	14	2.50	1.00	14
D1	3.00	2.00	13	3.00	1.00	13	3.00	1.00	13	3.00	1.00	14
D2	3.50	1.00	14	3.00	1.00	13	3.00	1.25	12	3.00	2.00	14
E1	1.00	1.00	15	1.00	0.75	14	4.00	1.00	7	4.00	2.00	8
E2	1.00	1.00	14	1.00	1.00	14	4.00	1.00	7	4.00	2.00	9

	Monitorability					
	(1 — lower "very difficult", 5 — higher "very easy")					
	On — site food security			Off — site food security		
	Median	IQR	N	Median	IQR	N
Low-income countries	2.00	0.00	13	1.00	1.00	15
Middle-income countries	3.00	1.00	14	2.00	2.00	14
High-income countries	4.00	1.00	13	2.00	2.50	15

Table 6
Negative impacts on water security (feedstock-related).

Scenario	Probability			Reversibility		
	(1 — lower "very unlikely", 5 — higher "very likely")			(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N	Median	IQR	N
A1	3.00	1.00	14	3.00	1.25	12
A2	3.00	1.75	14	3.00	1.25	12
B1	2.50	1.00	12	3.00	2.00	12
B2	3.00	2.00	11	3.00	1.00	10
C1	3.00	2.00	11	3.00	1.00	11
C2	4.00	1.00	10	2.00	1.00	12
D1	2.00	1.00	10	3.00	1.00	12
D2	3.00	1.00	9	3.00	1.00	12
E1	1.00	1.75	14	4.00	1.25	8
E2	1.00	1.75	14	4.00	1.25	8

	Monitorability		
	(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N
Low-income countries	2.00	1.00	15
Middle-income countries	2.00	1.00	15
High-income countries	3.00	1.50	15

Again, the potential for implementing these mechanisms would be likely to correlate to economic development. Others indicated, however, that monitoring this particular variable can be rather complicated due to the complexity of the supply chain and its related markets.

4.2. Impacts on food security

Two dimensions of food security were explored in the study. The first referred to the impacts on local (on-site) food security at the site of production (i.e. equitable and sufficient access to food by locals from communities where feedstock for cellulosic ethanol may be produced). The second aimed to explore the effects of large-scale feedstock production for cellulosic ethanol on food security at a broader scale (off-site) (i.e. equitable and sufficient access to food by people, especially vulnerable groups, from other areas than feedstock hosting communities).

For both local and macro-level food security, the best-case scenarios (i.e. those where food security is perceived as being least threatened) were those in which MSW, otherwise destined to landfills, was used as feedstock for producing cellulosic ethanol, disregard the country of production (Table 5). Following these as second-level best-case scenarios, were those where feedstock is cultivated or collected in countries like the UK and the US. In contrast, scenarios where dedicated energy crops such as SRC and perennial grasses are grown in African countries, such as Uganda and Kenya, were perceived as being potentially detrimental to local food security. In this situation, cultivating these crops in land previously dedicated to other agricultural or forestry activities would likely be more menacing to on-site food security than doing it on degraded land. Indeed, one panellist suggested that growing energy crops on degraded land might "even have a positive impact on productivity due to an increase in the levels of nitrogen in the soil" (participant 14). There was less agreement regarding worst-case scenarios for macro-level food security than local food security in the expert group. Scenarios that rated slightly worse than others were again those where raw material for cellulosic ethanol is collected or cultivated in African countries.

Many factors play a role in food security levels, regarded by panellists as a complex issue, in which it is difficult to generalise. As one participant puts it, "attribution of food insecurity to biofuel production is contested and contestable, requiring isolation of interacting factors, often spatially and temporally remote from each other" (participant 15). As indicated by another expert, impacts on local food security will also depend on specific consumption baskets (share of the budget spent on food and consumed types of food), so they are likely to vary from place to place, among different classes or even ethnic groups within the local population. Experts also indicated that governments have an important role in guaranteeing food security by implementing social policies and regulating land-use. Examples offered refer to

Table 7
Negative impacts on water security (conversion processes).

Scenario	Probability			Reversibility			Monitorability		
	(1 — lower "very unlikely", 5 — higher "very likely")			(1 — lower "very difficult", 5 — higher "very easy")			(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N	Median	IQR	N	Median	IQR	N
Low-income countries	4.00	1.00	9	2.00	1.00	12	2.00	0.50	15
Middle-income countries	4.00	1.00	9	2.00	0.50	12	3.00	1.50	15
High-income countries	3.00	1.25	8	2.50	1.00	12	3.00	1.00	15

Table 8
Negative impacts on biodiversity security.

Scenario	Probability			Reversibility		
	(1 — lower "very unlikely", 5 — higher "very likely")			(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N	Median	IQR	N
A1	3.00	2.00	14	2.00	0.50	15
A2	3.00	1.75	14	2.00	0.50	15
B1	3.00	1.00	14	3.00	1.50	15
B2	3.00	1.00	14	2.00	1.00	14
C1	4.00	1.00	14	2.00	1.00	15
C2	4.00	0.75	14	2.00	0.75	14
D1	4.00	1.00	14	2.00	1.00	14
D2	4.00	1.00	14	2.00	0.75	14
E1	1.00	1.00	15	4.00	0.75	6
E2	1.00	1.00	15	3.50	1.00	6

	Monitorability		
	(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N
Low-income countries	1.00	1.00	15
Middle-income countries	2.00	1.50	15
High-income countries	2.00	1.00	15

Brazil's "bolsa família", which provides direct and continued financial help to impoverished families, and the national programme of sugarcane zoning that restricts cultivation of such feedstock to specific areas within the country.

In terms of re-establishing food security by mitigating the competition of cellulosic feedstock with food crops, experts considered the case where dedicated energy crops were grown on land dedicated to other activities in African countries as the hardest to manage, (i.e. lower reversibility, both for local and macro food security; Table 5). For residues and wastes the task was perceived as being easier, since farmers could just keep or plough the residues back into soil. However, some argued that it might take time to achieve the same harvest levels again. As for the monitorability of changes in the levels of food security there was agreement that local food security would be more difficult to monitor in African, low-income countries than in middle-income countries such as Brazil and high-income countries. In the case of the latter, experts considered monitoring as a relatively easy activity and perceived monitoring food security on a larger-scale to be significantly more difficult task than at the local level (Table 5).

4.3. Impacts on water security

Water security depends on several factors, including the actual demand for water for growing crops, for converting glucose into ethanol at the refinery and the potential water pollution from both stages. To try to capture this, the issue of water security was analysed in the survey using two variables corresponding to water use at the feedstock production phase and at the producing plant. Of all variables assessed by panellists, impacts on water security were by far the most uncertain (regarding the frequency with which experts would tick the "not sure" box), especially with regard to the stage of conversion processes. As indicated by one participant, "water impacts are considered as unknown by many" (participant 17).

Despite acknowledging these high levels of uncertainty, the majority of participants went on to rate the variable in each scenario. At the stage of feedstock production, converting land which had previously been devoted to other agricultural or forestry activities to dedicated energy crops in African countries was considered to be the worst-case scenario for water security (Table 6). Conversely, the cases of cultivated perennial grasses and collected residues in European countries, were forecasted to perform much more positively. One participant argued that feedstock types for cellulosic ethanol that require irrigation would be unlikely to become commercially viable and that "water quantity and quality will be generally improved by having more perennials on the landscape" (participant 4). However, as indicated by another panellist, additional irrigation might be needed if dedicated crops are planted in degraded land. For some participants, the amount of water used was seen to be much more dependent on agricultural practices and water management systems than crop feedstock selection; ultimately, any badly managed crop could have negative impacts on water security. For residues and wastes, water demand might be less of an issue, but "minimum amounts of residues must remain on the ground in order to protect it from erosion, loss of nutrients and water" (participant 14). Moreover, one should also consider that, in the future "climate change may reduce water availability in many regions" (participant 10).

Many experts were unsure about how conversion technologies would impact on water security. When converting cellulosic feedstock into ethanol, participants rated the case of low and middle-income countries equally, but above high-income countries in terms of probability of negative impacts on water security (Table 7). Factors raised as important to consider by participants were the size of the conversion plant, the specifics of the pre-treatment processes for the biochemical route, which "might use lots of water" (participant 4), whether water is recycled or not, and other baseline conditions such

Table 9
Exclusion of low-skilled workers in the stage of conversion processes.

Scenario	Probability			Reversibility			Monitorability		
	(1 — lower "very unlikely", 5 — higher "very likely")			(1 — lower "very difficult", 5 — higher "very easy")			(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N	Median	IQR	N	Median	IQR	N
Low-income countries	3.50	1.75	14	2.00	2.00	14	2.00	1.00	15
Middle-income countries	3.50	1.00	14	2.50	1.00	14	3.00	0.50	15
High-income countries	3.50	1.75	14	3.00	1.00	14	3.00	1.00	15

Table 10
Exclusion of small-scale producers in the supply chain of cellulosic ethanol.

Scenario	Probability			Reversibility			Monitorability		
	(1 — lower "very unlikely", 5 — higher "very likely")			(1 — lower "very difficult", 5 — higher "very easy")			(1 — lower "very difficult", 5 — higher "very easy")		
	Median	IQR	N	Median	IQR	N	Median	IQR	N
Low-income countries	4.00	1.50	15	2.00	1.50	14	3.50	1.75	14
Middle-income countries	4.00	1.50	15	2.00	1.50	14	3.50	1.00	14
High-income countries	4.00	2.00	15	3.00	1.00	14	4.00	0.75	14

as local water availability and the amount of toxic water that is discharged in waterways.

Re-establishing water security was regarded as being moderately difficult to difficult in all scenarios (Tables 6 and 7). Participants indicated that technology improvements could play a decisive role in reducing water demand through improved efficiency, for example. For one of the panellists, if understood as mitigation potential, and from a technical standing point, reversibility would not differ much between scenarios in the stage of feedstock production. However, he added that, "the potential for actually fundamentally modifying the supply chain depends on so many factors that is rather hard to compare the scenarios" (participant 11).

Monitoring water demand and pollution at the feedstock production stage was considered to be more difficult than for the conversion phase (Tables 6 and 7). It could also vary between countries due to institutional capacity, which is thought to be higher in higher income countries. Experts suggested a range of quantitative and qualitative indicators and tools that could be used to monitor water use efficiency, such as water footprint and watertable (participant 23).

4.4. Impacts on biodiversity security

The potential social consequences that could be related to the impact of cellulosic ethanol production on biodiversity levels were defined in terms of biodiversity security. This is the preservation of plant and animal species that are valuable to human societies, or that could be valuable in the future. Examples of value include biological pest control functions or to maintain the flow of other ecosystem services. Compared to residue collection scenarios, panellists consider that the cultivation of dedicated energy crops is more likely to have negative impacts on biodiversity levels (Table 8). Here, experts did not differentiate between the country of production or the specific kind of crop being cultivated (e.g. SRC vs. perennial grasses). Several experts pointed out that the cultivation of such crops could favour the expansion of monocultures, inherently decreasing biodiversity levels. Moreover, the risk of negative impacts could be greater in low and middle-income countries, "as laws protecting forests in most developing countries are vague and inadequate" (participant 2). In contrast, some degree of dissent among experts was observed regarding the effects of collection of sugarcane straw in Brazil and African countries in threatening biodiversity. For example, one participant referred to the necessity of taking into account the intensity with which straw is harvested: "The impacts we perceive are low if the 'take' is moderate (say 30%–50%). […], Overstripping of crop residues will likely lead to soil carbon loss and increased biodiversity risk" (participant 16). Some experts indicated the importance of establishing a more detailed baseline scenario with which to work to assess the variable. As argued by another participant, "for energy crops, biodiversity impacts and reversibility largely depend on the baseline conditions […] this illustrates one of the main problems with bioenergy impact assessment – so much is site specific" (participant 15).

Panellists attributed very low reversibility for biodiversity levels for all scenarios[4] (Table 8), suggesting that mitigating a decrease on biodiversity levels would be a difficult or very difficult task. Of all impacts, biodiversity security is the variable that rates the lowest for reversibility, independent of the type of feedstock being collected or cultivated. As one expert puts it, "restoring prior biodiversity levels is not a very realistic scenario" (participant 10). Although participants rated all scenarios as equally low (i.e. same median value) the effects of the collection of straw in countries like the UK on biodiversity were perceived as being easier to mitigate compared to the rest of scenarios.

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[4] Except for collection of urban waste, which does not apply to this variable.

There was agreement on the difficulty of monitoring the loss of biodiversity (Table 8), considered by experts as one of the most difficult impacts to monitor, along with off-site food security. As indicated by a panellist, "it is very difficult to measure and monitor biodiversity, so we will have a difficult time saying anything definite about it" (participant 4). Additionally, monitoring biodiversity levels was perceived as being a harder task in low and middle-income countries than in high-income countries. Experts stressed that it can be a time-consuming, expensive activity that depends on prior-knowledge of species diversity or abundance and that requires skilled labour, among other factors.

4.5. Exclusion of low-skilled workers in the stage of conversion processes

The penultimate variable assessed by participants was the potential exclusion of low-skilled workers at the feedstock conversion stage. Experts who rated this variable considered that low-skilled workers will likely be excluded from the supply chain of cellulosic ethanol (Table 9). Median-values regarding the probability of this potential impact were the same for all three scenarios (i.e. low, middle and high-income countries). However, despite acknowledging the role of technological specialisation and the use of advanced systems, participants perceived the inclusion of low-skilled workers as an issue that is also very much dependent upon specific social circumstances and companies' policies. Accordingly, the existence of, for example, incentives to develop workers' skills and the ability of governments and companies to offer training would likely be decisive factors in determining the outcomes of the variable. As indicated by a panellist, "it depends on the context, there is nothing inherent in these jobs that excludes low-skilled workers if you are going to be putting in place training programs" (participant 18). In any case, participants seem to consider that this would be an easier process in high-income countries (Table 9). The difficulty of including low-skilled workers at the conversion processes stage should not, however, be regarded an exclusive issue of cellulosic ethanol. As pointed out by another panellist, "both first and second-generation processes are highly technical" (participant 7).

Monitoring the demand for and the inclusion of low-skilled workers in the supply chain of cellulosic ethanol was, comparatively, rated as being easier than for other impacts (Table 9). The same pattern applies for other variables appraised in the survey, i.e. monitoring of impacts was perceived to be an easier task in high-income countries than in middle and low-income countries due to issues of institutional capacity and availability of resources.

4.6. Exclusion of small-scale producers in the supply chain of cellulosic ethanol

Similar to the case of small-scale producers of feedstock, panellists considered that small-scale producers of ethanol, i.e. those involved with the conversion of feedstock into biofuel, are likely to be excluded from the supply chain of cellulosic ethanol (Table 10). Many pointed out the problem of unequal market competition with large-scale producers that could be faced by low-volume producers. Technical capability and costs to produce cellulosic ethanol were also identified as important factors that could hinder production at a smaller scale. As one expert illustrated, "the option [of including small-scale producers in the ethanol supply chain] was tested in the beginning of the 'Proalcool' programme [in Brazil], but did not stand the competition with large companies. […] In the case of second-generation, a technology more expensive than first-generation *per se*, competition will be even harder" (participant 14). Others considered that as with the inclusion of low-skilled workers, the exclusion of small producers might also depend on factors like the implementation of incentive structures by governments and the specific behaviour of companies. Rated as the easiest impact to monitor from all variables appraised in the Delphi survey, the task of monitoring is nevertheless considered to be more complicated in poorer countries (Table 10).

5. Limitations and strengths of the study

Valuable messages regarding the limitations of the study can be drawn from the survey process. One of the most relevant issues in this regard refers to the complexity of the variables assessed. The appraisal of simplified 'versions' of complex concepts — that rely on single instead of multiple indicators, was valuable to unveil the various factors considered and assumptions made by the participants. However, these proved to be hard to work with in the absence of better-defined scenarios, revealing the limitations of Delphi exercises in tapping generalised, yet complex realities. During the design of the survey, a major issue that emerged from the attempt to generalise social aspects related to a technological transition of ethanol was that every variable involves a context-dependent component. A non-exhaustive list would include factors such as a specific company's policies, facilities' characteristics and the environmental and social context of hosting communities. The problem of context-dependency was later corroborated in the exercise through various comments made by participants, regarding the difficulty they had for assessing variables under generic, technology-based scenarios. Feedback from the evaluation questionnaire also indicated that:

- Participants found it difficult to assess variables and support their opinion in the absence of evidence (since cellulosic ethanol is still being produced on an experimental stage), and making judgements under briefly described scenarios;
- The questionnaire was considered to be long and include complex questions, making participation in the survey rather time-demanding;
- The design of the survey did not allow space for a debate on the positive aspects of cellulosic ethanol and possible configurations of more sustainable biofuel systems.

One should note that the design and content of a Delphi study reflect the culture, bias and knowledge of its formulators (Linstone and Turoff, 2002:226). This is valid for both proponents and designers of the study and those who participate in it. Surveys will be always limited in the sense that specific choices made by a group of individuals will shape the exercise and, thus, influence its results. Besides, the study cannot claim to be representative in terms of the experts' community involved in it and the appraisal is constrained by the types of expertise of selected participants.

On the other hand, feedback from experts also indicates important strengths of the Delphi study in which they participated. They considered the results useful to inform other assessments of cellulosic ethanol and to inform decision-making on biofuel policy. Some also indicated that their participation in the Delphi helped them learning more about the topics addressed in the survey and made them feel more interested about the social dimension of the impacts of cellulosic ethanol. Other aspects pointed out by experts as the main strengths of the study include:

- Its strong interdisciplinary character given the broad range of expertise involved;
- The interactive component of the method as a tool for knowledge pooling;
- The opportunity of reflecting upon key issues concerning the social impacts of biofuels through comprehensive questions and interesting scenarios.

6. Key considerations on the development of cellulosic ethanol

The analysis of the results of the Delphi survey presented in Section 4 provides an opportunity to outline some important considerations regarding a transition to cellulosic ethanol with regard to its social sustainability.

6.1. Replacing the use of food crops, as feedstock in the production of conventional biofuels, for non-edible raw material to produce advanced biofuels such as cellulosic ethanol might not guarantee overcoming food security risks

Apart from the case where cellulosic ethanol is produced from the organic fraction of urban waste, there are doubts regarding the effects of its production from other feedstock on food security. Whereas the use of residues and wastes as raw materials for cellulosic ethanol raises less concern among experts (except for potential effects of the removal of residues on worsening soil conditions), growing dedicated energy crops such as SRC and perennial grasses is perceived as a more 'risky' option in terms of a potentially detrimental interference in the food chain. This is mostly related to the substitution of current agricultural activities by energy crops, lower levels of reversibility for such cropping activities and the potential use of land that could otherwise be suitable for food production. With regard to the latter, many advocate instead for the use of land considered to be low-input or 'marginal' as legitimate sites for growing dedicated energy crops for the production of cellulosic ethanol (e.g. Tilman et al., 2006; Gopalakrishnan et al., 2009; Swinton et al., 2011). However, in-depth analyses of the terminology demonstrate that such definitions are a matter of dispute and should be regarded with scepticism. As social constructs, they are ultimately created or adopted by certain groups of actors in order to defend their particular interests regarding land-use (Baka, 2014; Shortall, 2013).

6.2. Feedstock production for cellulosic ethanol is inserted in the same agricultural paradigm to that of conventional ethanol

An important result of the survey that helps to support this statement is the perception among participants of scenarios where cellulosic ethanol is produced from urban waste (which should not involve land-use change) as best-case scenarios or as scenarios that would not interfere at all with the variables assessed. Therefore, it seems logical to infer that the impacts of biofuels at the stage of feedstock production are very much related to the use of natural resources and changes in the use of land, irrespective of the type of feedstock being collected or cultivated. This inserts the case of biofuels in the same paradigm of any other agricultural activity, illustrated by the thesis of Beus and Dunlap (1990) as a dichotomy between conventional, industrialised and alternative, ecological agriculture. Issues such as the scale of production, the intensity in the use of fertilisers and herbicides, the expansion of monocultures, good or bad land management in terms of control of erosion – all highlighted by experts in the Delphi survey – are issues that also apply to agriculture overall. It is worth noting that such concerns might not be exclusive to first-generation biofuels nor might they be exclusive to growing dedicated energy crops, since bad practices in the collection of residues and wastes from agricultural and forestry activities could also entail negative environmental impacts on the soil and water. As indicated by experts in the survey, the replication of intensive, large-scale models of forestry and agricultural production in cellulosic ethanol production might lead to biodiversity losses and a decrease in the quality of water — impacts that are perceived as being potentially irreversible.

6.3. From the perspective of the inclusion of small landholders and small-scale producers in the supply chain, the contribution of cellulosic ethanol to rural development is uncertain

An important factor to be considered in this regard relates to the potentially high costs of feedstock production, both for collection of residues and wastes and cultivation of dedicated energy crops, and of conversion processes into ethanol. Experts from the US and Brazil that participated in the survey indicate that the supply chain of first-generation ethanol is already dominated by large-scale producers in both countries. Besides technology costs, free market competition could also favour large-scale producers due to demand for lower-price products in the ethanol supply chain. Compared to a highly centralised oil industry, which is controlled by few corporations, biofuel production is characterised by a considerably decentralised system. Experts pointed out at the proximity of processing facilities in relation to the localities where feedstock is produced as an additional and significant factor influencing costs. On the other hand, while decentralisation could represent an opportunity to local empowerment (Bailey et al., 2011), several participants in the Delphi indicated that governments and companies would have a decisive role in guaranteeing that the benefits are effectively extended to rural communities (also stressed by Bailey et al., 2011). As recent research shows, the interests of host communities could end up being at odds with the ones of the industry and of regional and local governments in the absence of specific initiatives and programmes aimed at empowering such communities (Ribeiro, 2013b).

6.4. The global South will likely experience the impacts of cellulosic ethanol production differently to the global North

As previously indicated, the outcomes of social change processes are likely to be experienced differently across different groups of actors and contexts. Such differences may be generalised to nations, due to considerable disparities in regard to their socioeconomic and political contexts. This should be just as true for advanced biofuels as it is for conventional ones. For all variables, scenarios that refer to high-income countries rate better than those involving middle and low-income countries. The trend is especially noticeable in ratings of the monitoring or mitigation capacity of impacts by different nations. For poorer countries, a lack of resources or corruption within the system could compromise the latter, in the opinion of experts. The burden of impacts is likely to also depend on specific baseline conditions. For example, since a larger part of the budget of poor people is spent on food (Aerni, 2008; Timilsina and Shrestha, 2011), rural communities from African countries might be more vulnerable to changes in food availability and prices. This statement is supported by the opinion of experts in the survey. Different political cultures could also influence outcomes due to both specific regulations to protect the people and the environment, and because of issues of law enforcement and regulatory compliance. Participants particularly acknowledged this point with regard to land-use practices, water management and biodiversity conservation, which could be more controversial in the global South. This has major implications for biofuel governance, especially regarding international markets and novel regulatory mechanisms and initiatives for 'ensuring' sustainability, such as certification schemes.

6.5. The appraisal of the impacts of advanced biofuels is a complex task

Several experts emphasised in the survey that the impacts of cellulosic ethanol production depend largely on the baseline conditions considered in appraisals. Despite the possibility of building on real data of studies on the impacts of conventional ethanol, such context-dependence suggests that the assessment of potential impacts of cellulosic ethanol before its implementation at a commercial scale involves high levels of uncertainty. Not only baseline conditions are unknown, but also the establishment of assumptions and boundaries of the system are steps in the design of the study that have great influence on its results. This is already acknowledged by lifecycle assessments (LCAs) of biofuels, especially in regard to the considerable number of competing results for GHG and energy balance of certain supply chains (see Larson, 2006; Cherubini et al., 2009; Borrion et al., 2012). In so far as any in-depth analysis of the social dimension of biofuels would depend on the establishment of a series of environmental, social, economic and technical parameters, the same difficulty or higher could be expected. Attempts to translate LCA into the social realm through systematising and accounting for the social impacts of products have resulted in interesting approaches (see, e.g. Jorgensen et al., 2008; Benoît et al., 2010). These studies however do not address other important aspects of the social dimension of technological change such as disputing interests and behaviour of specific actors, the public demand and acceptance of technology and the normative dimension of the appraisal. Further, LCAs and assessments have embedded assumptions that are hardly ever disclosed (Boucher et al., 2014). These are all relevant points of discussion regarding the variables assessed in the Delphi — such discussion, however, goes beyond the scope of the present study. More specific considerations around the challenges of appraising the social impacts of cellulosic ethanol include the uncertainty regarding the development of new markets around supply chains and their potential complexity; the unpredictable perception of investment risk by producers and difficulty in understanding the spatial and temporal dimensions of factors that interfere with variables such as food security. In this line, "biofuel impact assessment continues to push the limits of impact assessment methods" (Upham and Smith, 2014:267).

7. Conclusions

The process of reflection and discussion on the different scenarios for cellulosic ethanol production allowed experts that participated in the Delphi survey presented in this paper to disclose some of the main assumptions that would guide their ratings, and important factors that play a role in the social impacts assessed. Their comments support the claim that assessing the social sustainability of a development such as cellulosic ethanol is not a straightforward task, and that outcomes are largely context-dependent. Since cellulosic ethanol is yet to be produced at a commercial level, there are also high levels of uncertainty and ignorance surrounding its potential social and environmental impacts. The occurrence and severity of impacts are associated with different processes of land-use change, types of feedstock used and to the different nations in which production of raw material for cellulosic ethanol or the production of the biofuel itself might take place. In general, the use of waste and residues as feedstock for cellulosic ethanol production is perceived as preferable over the use of dedicated energy crops. Also, low and middle-income countries of the global South are seen as more vulnerable to negative impacts than high-income countries from the global North. However, apart from the case of cellulosic ethanol produced from urban waste, all potential supply chains may face the same societal and environmental challenges faced by conventional ethanol. These are related to doubts regarding their potential to contribute to rural development, possible detrimental effects of land-use change and potentially negative impacts on biodiversity and water.

Although the production of cellulosic ethanol has not yet reached large-scale proportions, it is the intention of the industry to reduce costs and make its commercial deployment viable. Meanwhile, demonstration facilities and policy incentives provide the opportunity for other technologies, markets and social actors to evolve from and get involved with the development of cellulosic ethanol. With reservations concerning potentially deterministic views on technological change, the social control over technologies tends to diminish in face of the continued development and increased complexity of sociotechnical systems. This has been an acknowledged fact for many decades (see, e.g. Collingridge, 1980) and is relevant for the social appraisal of emerging science and technological developments such as the case of cellulosic ethanol. Participants in the Delphi supported this statement by pointing out at several issues that relate to aspects of reversibility of the technical system and to institutional capacities and political cultures of nations where projects could be implemented. This suggests an extension of the thesis of the social construction of technology to the governance of its potential impacts. Not only our capacity of controlling technological change is diminished in face of complexity, but also our chances of properly governing or avoiding its impacts might be lower. In this sense, negotiating technical options ultimately means governing also their related social change processes. As argued by Winner (2001), boosting, not constraining negotiation possibilities in the appraisal of energy alternatives, should be the tendency here. The development of each alternative, e.g. cellulosic ethanol or other advanced biofuels, should be viewed as a multidirectional process (see Pinch and Bijker, 1993). As such, different technologies and technological pathways are seen as being possible and each requires appraisal from a range of relevant actors. It is highly desirable that assessments involve affected or interested actors, beyond disciplinary experts. As it is shown for the case of cellulosic ethanol, specific environmental and social contexts have to be considered in their singularity and real case studies should not obviate this.

From the analysis of some of its potential social impacts, this study does not provide an answer on which is the 'best' way to take regarding the development of cellulosic ethanol. It attempts to offer, instead, a few messages to technology developers and decision-makers. Innovations in biofuel technologies might be motivated by different concerns, such as sustainability issues, the prospect of new markets and consumer demand. The former has taken on a particular political relevance in the EU. However, while much of the 'ability' of innovations in addressing concerns such as sustainability relies on important technical features of developments like, for example, the notion of efficiency or reversibility, it also depends on contextual, societal factors (Quintanilla, 1993, 2005). In this sense, behind the positive and negative outcomes of scientific and technological developments are the mechanisms responsible for governing their production, applications and impacts. Such mechanisms are embedded in different scientific and political cultures, which will ultimately influence their consequences on society and on the environment. Therefore, deciding on energy futures is not only a matter of responsibility of technology developers, funders and users, but also of political commitment to more participatory, comprehensive and transparent practices in the appraisal of technological change. It is crucial to evaluate *if* and *how* the production of cellulosic ethanol would help overcoming the various issues that have already been raised and evidenced for the production of conventional biofuels. More adequate regulatory measures and incentive mechanisms would follow. The results of the Delphi study presented in this paper suggest that in this regard important challenges remain. If these are not properly addressed, there is a risk that advanced biofuels such as cellulosic ethanol will not be justifiable from a sustainability standing point — something that would ultimately undermine the legitimacy of its political support.

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References

Aerni, P., 2008. A new approach to deal with the global food crisis. ATDF J. 5 (1/2), 16–31.

Ajanovic, A., 2011. Biofuels versus food production: does biofuels production increase food prices? Energy 36 (4), 2070–2076.

Bailey, C., Dyer, J.F., Teeter, L., 2011. Assessing the rural development potential of lignocellulosic biofuels in Alabama. Biomass Bioenergy 35 (4), 1408–1417.

Baines, J., Baker, J., Brophy, L., Rielly, A., Thompson, J., Yasin, Y., 2012. Social monitoring can contribute to ex-ante SIAs: a case of New Zealand wind farm planning. Impact Assess. Proj. Apprais. 30 (3), 195–206.

Baka, J., 2014. What wastelands? A critique of biofuel policy discourse in South India. Geoforum 54, 315–323.

Barben, D., Fisher, E., Selin, C., Guston, D.H., 2008. Anticipatory governance of nanotechnology: foresight, engagement, and integration. In: Hackett, Edward J., Amsterdamska, Olga, Lynch, Michael, Wajcman, Judy (Eds.), The Handbook of Science and Technology Studies. The MIT Press, Cambridge, Massachusetts and London, pp. 979–1000.

Becker, H.A., 2001. Social impact assessment. Eur. J. Oper. Res. 128, 311–321.

Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., Prakash, S., Ugaya, C., Beck, T., 2010. The guidelines for social life cycle assessment of products: just in time! Int. J. Life Cycle Assess. 15, 156–163.

Beus, C.E., Dunlap, R.E., 1990. Conventional versus alternative agriculture: the paradigmatic roots of the debate. Rural. Sociol. 55, 590–616.

Bijker, W.E., Bal, R., Hendriks, R., 2009. The Paradox of Scientific Authority: the Role of Scientific Advice in Democracies. The MIT Press, Cambridge.

Borrion, A.L., McManus, M.C., Hammond, G.P., 2012. Environmental life cycle assessment of bioethanol production from wheat straw. Biomass Bioenergy 47, 9–19.

Boucher, P., Smith, R., Millar, K., 2014. Biofuels under the spotlight: the state of assessment and potential for integration. Sci. Public Policy 41 (3), 283–293.

Bryman, A., 2012. Social Research Methods, 4th ed. Oxford University Press, Oxford.

Burdge, R., Robertson, R.A., 1990. Social impact assessment and the public involvement process. Environ. Impact Assess. Rev. 10, 81-80.

Buytaert, V., Muys, B., Devriendt, N., Pelkmans, L., Kretzschmar, J.G., Samson, R., 2011. Towards integrated sustainability assessment for energetic use of biomass: a state of the art evaluation of assessment tools. Renew. Sust. Energ. Rev. 15, 3918–3933.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resour. Conserv. Recycl. 53, 434–447.

Clason, D.L., Dormody, T.J., 1994. Analyzing data measured by individual Likert-type items. J. Agric. Educ. 35 (4), 31–35.

Collingridge, D., 1980. The Social Control of Technology. Frances Pinter, London.

Cuhls, K., 2003. From forecasting to foresight processes — new participative foresight activities in Germany. J. Forecast. 22, 93–111.

Dalkey, N., Helmer, O., 1963. An experimental application of the Delphi method to the use of experts. Manag. Sci. 9 (3), 458–467.

Doornbosch, R., Steenblik, R., 2007. Biofuels: is the Cure Worse than the Disease? Roundtable on Sustainable Development/OECD, Paris.

Dovers, S.R., 1995. A framework for scaling and framing policy problems in sustainability. Ecol. Econ. 12, 93–106.

Esteves, A.M., Franks, D., Vanclay, F., 2012. Social impact assessment: the state of the art. Impact Assess. Proj. Apprais. 30 (1), 34–42.

European Commission, 2013. European Parliament resolution of 11 September 2013 on the proposal for a directive of the European Parliament and of the Council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 299/28/EC on the promotion of the use of energy from renewable sources, (P7 TA(2013)0357).

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M., 2006. Ethanol can contribute to energy and environmental goals. Science 311, 506–508.

Faruk, A.C., Lamming, R.C., Cousins, P.D., Bowen, F.E., 2002. Analyzing, mapping and managing environmental impacts along supply chains. J. Ind. Ecol. 5 (2), 13–36.

González-García, S., Moreira, M.T., Feijoo, G., 2010. Comparative environmental performance of lignocellulosic ethanol from different feedstocks. Renew. Sust. Energ. Rev. 14, 2077–2085.

Gopalakrishnan, G., Negri, M.C., Wang, M., Wu, M., Snyder, S.W., Lafreniere, L., 2009. Biofuels, land and water: a systems approach to sustainability. Environ. Sci. Technol. 43, 6094–6100.

Green, H., Hunter, C., Moore, B., 1990. Assessing the environmental impact of tourism development: the use of the Delphi technique. Tour. Manag. 11 (2), 111–120.

Hahn-Hägerdal, B., Galbe, M., Gorwa-Grauslund, M.F., Lidén, G., Zacchi, G., 2006. Bioethanol — the fuel of tomorrow from the residues of today. Trends Biotechnol. 24 (12), 549–556.

Hasson, F., Keeney, S., 2011. Enhancing rigour in the Delphi technique research. Technol. Forecast. Soc. Chang. 78, 1695–1704.

Hussler, C., Muller, P., Rondé, P., 2011. Is diversity in Delphi panelist groups useful? Evidence from a French forecasting exercise on the future of nuclear energy. Technol. Forecast. Soc. Chang. 78, 1642–1653.

Jorgensen, A., Le Bocq, A., Nazarkina, L., Hauschild, M., 2008. Methodologies for social life cycle assessment. Int. J. Life Cycle Assess. 13, 96–103.

Kaercher, J.A., Schneider, R.C.S., Klamt, R.A., Da Silva, W.L.T., Schmatz, W.L., Szarblewski, M.S., Machado, E.L., 2013. Optimization of biodiesel production for self-consumption: considering its environmental impacts. J. Clean. Prod. 46, 74–82.

Kumar, S., Singh, S.P., Mishra, I.M., Adhikari, D.K., 2009. Recent advances in production of bioethanol from lignocellulosic biomass. Chem. Eng. Technol. 32 (4), 517–526.

Landeta, J., 2005. Current validity of the Delphi method in social sciences. Technol. Forecast. Soc. Chang. 73, 467–482.

Larson, E.D., 2006. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy Sustain. Dev. 10, 109–126.

Lawrence, D.P., 1997. Quality and effectiveness of environmental impact assessments: lessons and insights from ten assessments in Canada. Proj. Apprais. 12 (4), 219–232.

Limayen, A., Ricke, S.C., 2012. Lignocellulosic biomass for bioethanol production: current perspectives, potential issues and future prospects. Prog. Energy Combust. Sci. 38, 449–467.

Linstone, H.A., Turoff, M., 2002. The Delphi Method. Techniques and Applications. Institute of Technology (electronic book), New Jersey.

Linstone, H.A., Turoff, M., 2011. Delphi: a brief look backward and forward. Technol. Forecast. Soc. Chang. 78, 1712–1719.

Loveridge, D., Saritas, O., 2012. Ignorance and uncertainty: influences on future-oriented technology analysis. Tech. Anal. Strateg. Manag. 24 (8), 753–767.

Mabee, W.E., McFarlane, P.N., Saddler, J.N., 2011. Biomass availability for lignocellulosic ethanol production. Biomass Bioenergy 35, 4519–4529.

Matheson, S., Lence, B., Furst, J., 1997. Distributive fairness considerations in sustainable project selection. Hydrol. Sci. J. 42 (2), 531–548.

Menon, V., Rao, M., 2012. Trends in bioconversion of lignocellulose: biofuels, platform chemicals and biorefinery concept. Prog. Energy Combust. Sci. 38, 522–550.

Mohr, A., Raman, S., 2013. Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Energy Policy 63, 114–122.

Naik, S.N., Goud, V.V., Rout, P.K., Dalai, A.K., 2010. Production of first and second generation biofuels: a comprehensive review. Renew. Sust. Energ. Rev. 14, 578–597.

Parente, R., Anderson-Parente, J., 2011. A case study of long-term Delphi accuracy. Technol. Forecast. Soc. Chang. 78, 1705–1711.

Pinch, T.J., Bijker, W.E., 1993. The social construction of facts and artifacts: or how the Sociology of Science and the Sociology of Technology might benefit each other. In: Bijker, Wiebe E., Hughes, Thomas P., Pinch, Trevor J. (Eds.), The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology. The MIT Press, Cambridge, Massachusetts and London, England, pp. 17–50.

Quintanilla, M.A., 1993. The design and evaluation of technologies: some conceptual issues. In: Mitcham, C. (Ed.), Philosophy of Technology in Spanish Speaking Countries. Kluwer Academic Publishers, Dordrecht, pp. 173–195.

Quintanilla, M.A., 2005. Tecnología: un enfoque filosófico y otros ensayos de filosofía de la tecnología. Fondo de Cultura Económica, México, D.F.

Raikes, P., Jensen, M.F., Ponte, S., 2000. Global commodity chain analysis and the French filière approach: comparison and critique. Econ. Soc. 29 (3), 390–417.

Renewable Fuels Association, 2012. 2012 World Fuel Ethanol Production. Available at: http://ethanolrfa.org/pages/World-Fuel-Ethanol-Production (last accessed on 1 February 2014).

Ribeiro, B.E., 2012. From first to second generation biofuels: putting social aspects on the scale. In: Agustoni, A., Maretti, M. (Eds.), Energy Issues and Social Sciences. Theories and Applications. McGraw-Hill, Milan, pp. 79–94.

Ribeiro, B.E., 2013a. Beyond commonplace biofuels: social aspects of ethanol. Energy Policy 57, 355–362.

Ribeiro, B.E. (2013b), "What matters for host communities of biofuel projects: local public perception of ethanol in Spain". *Unpublished raw data*.

Rowe, G., Wright, G., 1999. The Delphi technique as a forecasting tool: issues and analysis. Int. J. Forecast. 15, 353–375.

Sanchez, O., Cardona, C., 2008. Trends in biotechnological production of fuel ethanol from different feedstocks. Bioresour. Technol. 99, 5270–5295.

Scapolo, F., Miles, I., 2006. Eliciting experts' knowledge: a comparison of two methods. Technol. Forecast. Soc. Chang. 73, 679–704.

Scharlemann, J.P.W., Laurance, W.F., 2008. How green are biofuels? Science 319, 43–44.

Selfa, T., Kulcsar, L., Bain, C., Goe, R., Middendorf, G., 2011. Biofuels Bonanza?: Exploring community perceptions of the promises and perils of biofuels production. Biomass Bioenergy 35, 1379–1389.

Shortall, O.K., 2013. "Marginal land" for energy crops: exploring definitions and embedded assumptions. Energy Policy 62, 19–27.

Sims, R.E.H., et al., 2010. An overview of second generation biofuel technologies. Bioresour. Technol. 101, 1570–1580.

Solomon, B.D., Barnes, J.R., Halvorsen, K.E., 2007. Grain and cellulosic ethanol: history, economic and energy policy. Biomass Bioenergy 31, 416–425.

Sun, Y., Cheng, J., 2002. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresour. Technol. 83, 1–11.

Swinton, S.M., Babcock, B.A., James, L.K., Bandaru, V., 2011. Higher US crop prices trigger little area expansion so marginal land for biofuel crops is limited. Energy Policy 39, 5254–5258.

Tichy, G., 2004. The over-optimism among experts in assessment and foresight. Technol. Forecast. Soc. Chang. 71, 341–363.

Tilman, D., Hill, J., Lehman, C., 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314, 1598–1600.

Timilsina, G.R., Shrestha, A., 2011. How much hope should we have for biofuels? Energy 36 (4), 2055–2069.

Tran, T.A., Daim, T., 2008. A taxonomic review of methods and tools applied in technology assessment. Technol. Forecast. Soc. Chang. 75, 1396–1405.

Upham, P., Smith, B., 2014. Using the Rapid Impact Assessment Matrix to synthesize biofuel and bioenergy impact assessment results: the example of medium scale bioenergy heat options. J. Clean. Prod. 65, 261–269.

Van den Ende, J., Mulder, K., Knot, M., Moors, E., Vergragt, P., 1998. Traditional and modern technology assessment. Towards a toolkit. Technol. Forecast. Soc. Chang. 58 (1/2), 5–21.

Van Schooten, M., Vanclay, F., Slootweg, R., 2003. Conceptualizing social change processes and social impacts. In: Becker, Henk A., Vanclay, Frank (Eds.), The International Handbook of Social Impact Assessment: Conceptual and Methodological Advances. Edward Elgar, Cheltenham, Reino Unido, pp. 74–91.

Vanclay, F., 2002. Conceptualising social impacts. Environ. Impact Assess. Rev. 22, 183–211.

Vanclay, F., 2003. International principles for social impact assessment. Impact Assess. Proj. Apprais. 21 (1), 5–11.

Verbruggen, A., 2013. Revocability and reversibility in societal decision-making. Ecol. Econ. 85, 20–27.

Viikari, L., Vehmaanpera, J., Koivula, A., 2012. Lignocellulosic ethanol: from science to industry. Biomass Bioenergy 46, 13–24.

Vizayakumar, K., Mohapatra, P.K.J., 1992. Environmental impact analysis of a coalfied. J. Environ. Manag. 34, 79–103.

Winner, L., 2001. Where technological determinism went. In: Cutcliffe, Stephen H., Mitcham, Carl (Eds.), Visions of STS: Counterpoints in Science, Technology and Society Studies. State University of New York Press, Albany, pp. 11–17.

Wright, W., Reid, T., 2011. Green dreams or pipe dreams? Media framing of the U.S. biofuels movement. Biomass Bioenergy 35, 1390–1399.

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