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# The challenge of measuring biofuel sustainability: A stakeholder-driven approach applied to the French case

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## A B S T R A C T

Measuring biofuel sustainability requires dealing with a wide variety of complex and conflicting values at stake. Consequently, the biofuel capacity to contribute to one specific value cannot lead to any absolute conclusion about the overall sustainability of biofuel. The scope of the sustainability concept may vary depending on individuals' preferences, the time scale and the geographical region. Based on the 5 pillars sustainability concept that includes social, economic, environmental, legal and cultural considerations, the present study proposes to assess several biofuel sustainability options for France by 2030 through a stakeholder-driven approach. Rather than seeking to reach a consensus, our approach allows us to capture the wide diversity of stakeholders' perspectives and preferences. French stakeholders perceive 22 different sustainability criteria for biofuels with a very low level of agreement between the different segments of professions (feedstock producers, biofuel producers, refining industry, fuel distributors, car manufacturers, end-users, government and NGOs). In order to operationalize the sustainability assessment, a set of indicators has been identified with stakeholders that allows us to measure the capacity of biofuels to fulfill each of their criteria. Seventeen biofuel options were assessed with regards to economic, social, environmental, cultural and legal considerations, allowing the identification of the strengths and weaknesses of each biofuel.

## 1. Introduction

In 1992, the European Common Agricultural Policy (CAP) introduced a set-aside measure to face the agricultural overproduction crisis but non-food usage crops were exempted. Since then, France has supported biofuel development in order to create new market opportunities for the agro-food industry. Relying on environmental sustainability considerations, especially for CO<sub>2</sub> emissions, the European parliament promoted a directive in 2003 (2003/30/EC) to support biofuel deployment. The directive required the Member States to ensure that renewable energy account for at least 5.75% of energy consumption in the transport sector by 2010. However, rising concerns about biofuel socio-environmental sustainability led to the addition of qualitative criteria to quantitative ones in 2009 through the Renewable Energy Directive (RED) [33]. The RED requires the Member States to reach a 10% share of renewable energy in the transport sector by 2020 with respect to several sustainability criteria. Three years later, the

European Commission proposed limiting the contribution of food crop based biofuels to a level of 5% because of direct and indirect land use change impacts (ILUC). According to the European Commission, despite a 10 billion euro per year public subsidy, the 2010 objective was not reached. Furthermore, without a massive contribution of food crops based biofuels, the attainment of the objective by 2020 is also highly uncertain. Consequently, the limit was increased to 7% in 2015 after three other years of conflicting debates between the different stakeholders. In the same year, the promotion of renewable energy was intensified and now includes a 15% sub-target by 2030 within the transport sector.

### 1.1. Biofuels and sustainability

Over the last decade, biofuels were perceived as one of the most sustainable alternatives to fossil fuels for transportation but due to several socio-environmental issues, this positive image has dramati-

cally changed [48]. Although biofuel deployment creates and maintains jobs, diversifies fuels and promotes renewable energy consumption, several drawbacks have been highlighted such as rising food prices, the land grabbing phenomena and ILUC [104,16,48,53]. Indeed, biofuel deployment is not just about energy but also about agricultural sector support, global trade food impacts and land use issues [70]. The biofuel support means an overlapping of several policies and measures with complex interactions. The biofuel policy impacts are still highly uncertain being neither linear nor proportional while depending on local, national and international contexts [24]. The biofuel capacity to fulfill one specific objective cannot lead to any absolute conclusion about its overall sustainability and whether it has a positive or negative impact.

Focusing on the French context, biofuel deployment was successively an agricultural sector support, an energy independence objective and finally an environmental and a bioeconomy issue. Therefore, defining a set of relevant sustainability criteria is necessary for the planning of the stages for renewable energy deployment [39], especially for biofuels [80,118]. Indeed, complex ecological and environmental problems such as biofuel systems are characterized by a diversity of conflicting values at stake associated with high uncertainties [25,115]. According to Athanasios Angelis-Dimakis [9], there is no standardized methodology that can be used to assess energy systems sustainability. Consequently, researchers have to design their approach depending on their specific objectives [82].

## 1.2. Objectives

Literature provides a wide range of papers that aim at assessing the sustainability of biofuel [109,114,29,47,76]. Several papers focus on specific criteria such as GHG mitigation ([31,52,55,75,85,106]), ILUC impact [117,17,27,41,6,74], as well as the impact on food prices [125,62,7,88], etc. Other papers focus on a wider range of sustainability criteria, but for a particular biofuel option [123,28,81,90,94,116]. The sustainability assessment of biofuels requires dealing with a wide range of criteria, whether economic, social, environmental or legal issues [115,48,80]. To our knowledge, there is currently no review that proposes bringing together in one paper the sustainability assessment of conventional and advanced biofuels (17 options) on the basis of a large range of criteria (22 criteria). Through a stakeholder-driven approach, we aim to propose such a review which furthermore is complemented by expert consultations. On the one hand, our paper relies on a wide range of literature that focuses on the identification of sustainability criteria within a bioenergy-system, which led us to deploy a stakeholder-driven approach [115,21,38,80]. On the other hand, given the large number of biofuels and criteria that were considered, we mobilized a wide range of literature concerning economic, social, environmental, legal and technical issues.

Through semi-structured interviews, the present study provides a basis to clearly identify criteria for inclusion in a sustainability assessment that reflect the whole biofuel system from the different perspectives of French stakeholders. The next section presents the theoretical background that led us to develop a stakeholder-driven approach to assess the biofuel system in France. Section 3 presents the identification of sets of biofuels, sustainability criteria and their associated indicators. Finally, Section 4 provides the sustainability assessment of the different identified biofuel options based on their capacity to fulfill the sustainability criteria of French stakeholders.

## 2. Theoretical background

### 2.1. The sustainability concept

The concept of sustainability was first defined in 1987 by the Brundtland Commission [20] through the sustainable development definition: “a development that meets the needs of the present without

compromising the ability of future generations to meet their own needs”. To achieve and maintain sustainability objectives, policy-makers require information to demonstrate whether the complex human system is becoming more or less sustainable [83]. Consequently, implementing sustainability policies requires the operationalization of the concept [100]. In order to operationalize sustainability measurement of the human-environment system, criteria have to be identified, long-term perspective and uncertainty have to be considered while keeping the whole framework manageable [21].

According to Pope et al. [95], the scope of the concept depends on the characteristics of the dimensions incorporated which are the basis of the sustainability assessment. Single pillar concepts were the oldest and primarily focus on the ecological impacts while socio-economic ones are seen as secondary and should never take priority over ecological preservation [38]. Two-pillar concepts focus on the balance between economic growth and ecological integrity regardless of social factors which are otherwise considered in the well-known three-pillar concepts [95]. By including cultural and institutional dimensions, four and five-pillar approaches have also been developed to broaden the scope of the sustainability concept [92].

Fundamentally, the concept of sustainability implies defining: what is to be sustained? What is to be developed? How is it possible to balance present and future needs [19,92]. However, due to the ambiguity of the scope of sustainable development, i.e. multiple and overlapping objectives, data availability, uncertainty and measurement methods, more than 500 concepts have been developed [92]. Although no clear consensus has emerged about sustainability indicator sets, according to Mayer [83], the sustainability of the complex human-based system is determined through both natural and anthropogenic resilience, desirability to human societies, as well as temporal and spatial scale boundaries. Both resilience and desirability determine sustainability objectives and the temporal and spatial scales define the extent of the system. The scope of the sustainability concept, objectives and indicators may vary depending on the expertise, the preferences of individuals and the geographical region [21]. Consequently, stakeholder-based approaches may help in identifying and structuring the multiple and sometimes conflicting perspectives of actors for sustainability assessment with regard to the temporal and spatial scales [114,21,25,38].

### 2.2. The Stakeholder-driven approach to measuring sustainability

Depending on the problem characteristics, stakeholder participation can take many forms and different degrees of involvement ranging from informing the public to co-producing knowledge and policy plans [115,25,68]. When focusing on sustainability problems, participation helps structuring and improving understanding of both the problem and its potential solutions by considering, articulating and evaluating divergent perspectives [25,54]. Based on Brodbeck et al. [18], such an approach requires involving heterogeneous stakeholder groups with different backgrounds, knowledge and expertise to facilitate mutual learning and to produce new insights. Moreover, marginal perspectives and viewpoints of unorganized stakeholder groups also need to be considered, especially within sustainability problems [57,89]. Consequently, rather than seeking to reach a consensus, stakeholder participation allows for the diversity of perspectives and preferences to be captured [51]. Indeed, stakeholder based methods that are aimed at reaching a consensus often fail in capturing the whole variety of viewpoints [25].

The literature provides a wide range of stakeholder-based approaches for addressing complex sustainability problems. Buchholz et al. [21] proposed analyzing the level of agreement and uncertainty concerning 35 sustainability criteria for bioenergy through an international expert survey composed of government, industry, academia, consulting and NGO representatives. Only 2 of the 35 proposed criteria were perceived as critical by more than a half of the 137 respondents.

Considering the lack of consensus, they suggested further debate and exchange among experts. Van Dam and Junginger [115] proposed analyzing the need to come to a harmonization of certification systems in the European Union through recommendations from a stakeholder questionnaire. The 473 respondents were from 34 countries and were represented by 6 stakeholder groups: NGOs, the policy sector, R & D, bioenergy producers, end-users and traders. Gallego Carrera and Mack [38] proposed an expert-based set of social indicators for the sustainability assessment of energy systems. The 39 respondents were composed of energy industry, political and administrative institutions, end user and environmental associations, as well as trade unions. Kern and Smith [69] have analyzed 27 semi-structured personal interviews within the Netherlands energy transition project carried out by the Ministry of Economic Affairs. Four stakeholder groups were represented in the study: policy makers, NGOs, researchers and businesses, all being interviewed.

Through a stakeholder-driven approach that includes 8 different stakeholder groups, the next section provides a basis to clearly identify criteria and their associated indicators for inclusion in a sustainability assessment of several biofuel options by 2030.

### 3. Selection of the set of indicators for the assessment of biofuel sustainability

As mentioned previously, the relevance of sustainability criteria depends on the points of view and cultural background of the stakeholders [21,73]. Based on the elaboration of the corresponding evaluation criteria associated with measurement scales, i.e. indicators, biofuel sustainability can be appropriately assessed. By applying a participatory process, the sustainability indicator set is discussed and reviewed by relevant and representative stakeholders in order to satisfy social acceptance requirements, i.e. legitimizing and ensuring that indicators fit their sustainability conception [38]. The stakeholder sustainability criteria can be revealed from the consequences of biofuels deployment, namely the bottom-up approach [102], and through the decomposition of the sustainability biofuel goal in sub-objectives, namely the top-down approach [67,103]. Both methods are not mutually exclusive and can even be complementary [73] such as in the present paper.

#### 3.1. Questionnaire structure

Stakeholders were individually asked to respond to a questionnaire (Table 1) through face-to-face meetings or call conferences split between a 30-min structured questionnaire and an unlimited and unstructured discussion concerning biofuel sustainability.

Table 1 presents the questionnaire structure. Part I focuses on determining the background of stakeholders. Next, on the basis of the

**Table 1**  
Questionnaire structure.

Part	Questions / From your perspective...
<b>Part I</b>	<b>About you, your organization</b> <i>Name, organization, job title, organizational position on biofuels in France</i>
<b>Part II</b>	<b>Review and definition of the set of biofuel options</b> <i>Scoring biofuel options from not at all to large-scale deployment</i>
<b>Part III</b>	<b>Review and definition of the set of biofuel options</b> <i>Including economic, social, environmental, technical, and legal issues</i>
<b>Part IV</b>	<b>Stakeholder group identification</b> <i>Individuals or group of individuals who might affect or might be affected by the consequences of biofuel deployment</i>

bottom-up approach proposed by Roy [102], Part II consists of identifying the set of the relevant biofuel options to consider by 2030. Part III aims at identifying and formulating sustainability criteria starting from the impacts of biofuels while respecting methodological requirements (adapted from Buchholz et al. [21]; Gallego Carrera and Mack [38]; Keeney and Raiffa, [67]):

- **Completeness:** through the participatory process, completeness requires that all the relevant points of view be captured;
- **Operationality:** the set of criteria should be measured on an appropriate scale while ensuring both data and information availability;
- **Non-redundancy:** within each stakeholder group, sustainable criteria should not measure the same thing;
- **Homogeneity:** within each stakeholder group, an agreement about the set of criteria group can be reached.

According to Munda [89], researchers are the most relevant individuals for formulating sustainability criteria with respect to methodological requirements. Based on literature, a set of sustainability criteria were provided to stakeholders for review and discussion [21]. Considering the participatory process, stakeholders were obviously allowed to suggest additional sustainability criteria, biofuel options and stakeholder groups as long as they were relevant.

Finally, given the above mentioned “completeness requirement”, Part IV aims to define which relevant stakeholders to consider within the biofuel-system in order to adequately assess its sustainability. Based on the methodology proposed by Munda [89], an analysis of historical legislative, research and administrative documents complemented with in-depth interviews of relevant stakeholders were carried out. Based on Macharis et al. [78], the present paper refers to relevant stakeholders as individuals or groups of individuals who might affect or might be affected by the consequences of biofuel deployment.

#### 3.2. Study population

Based on literature review [112,115,21,24], 7 stakeholder groups were initially considered: feedstock producers, biofuel producers, fuel distributors, end users, car manufacturers, government and NGOs. However, by taking into account the suggestions of stakeholders (Part IV), the refining industry was added to cope with the completeness requirement. Moreover, 11 biofuel experts were consulted in order to assess the biofuel capacity to fulfill the stakeholder sustainability criteria.

1. Feedstock producers included the biomass-based industry, French agricultural unions and feedstock traders;
2. The biofuel industry was represented by biotechnology companies and the unions of French biofuel producers;
3. The refining industry was represented by the oil-refining industry and the biorefinery industry;
4. Fuel distributors included the petroleum industry and large-scale retailers which share the French fuel distribution market (respectively 37.4% and 62.6%);
5. The end-users perspective was assessed through the French car users association. Other end-users associations were contacted but they mentioned a lack of knowledge as to why they did not contribute to the study;
6. Car manufacturers were represented by French car manufacturing union and a car manufacturer;
7. The government included specialized energy and environmental institutions and the French agricultural, energy, ecological and finance ministries;
8. NGOs were represented by socio-environmental and energy oriented non-governmental associations to capture the sustainability criteria of unorganized groups such as food security for the population of the

**Table 2**  
Biofuel set submitted to stakeholders' review.

Biofuel options by 2030	Feedstocks	Stakeholders' opinions		
		Agree	Neither	Disagree
<b>First generation biofuels (conventional biofuels)</b>				
Biodiesel	Rapeseed	88,5%	3,8%	7,7%
	Sunflower	84,6%	3,8%	11,5%
	Soybean (imported)	84,6%	7,7%	7,7%
	Palm (imported)	84,6%	7,7%	7,7%
Ethanol	Wheat	88,5%	3,8%	7,7%
	Corn	88,5%	3,8%	7,7%
	Sugar beet	84,6%	7,7%	7,7%
	Sugar cane (imported)	84,6%	7,7%	7,7%
Hydrotreated Vegetable Oil (HVO)	Rapeseed (imported)	65,4%	19,2%	15,4%
	Palm (imported)	65,4%	19,2%	15,4%
	Waste oils (imported)	69,2%	23,1%	7,7%
<b>Second generation biofuels (advanced biofuels)</b>				
Biodiesel	Agricultural residues	69,2%	15,4%	15,4%
	Forestry residues	69,2%	11,5%	19,2%
	Energy crops	53,8%	19,2%	26,9%
Lignocellulosic Ethanol	Agricultural residues	69,2%	15,4%	15,4%
	Forestry residues	69,2%	11,5%	19,2%
	Energy crops	53,8%	19,2%	26,9%
Bio-methane	Farm effluents, industrial wastes	23,1%	7,7%	69,2%
<b>Third generation biofuels (advanced biofuels)</b>				
Biodiesel	Microalgae	53,8%	26,9%	19,2%
Ethanol	Microalgae	46,2%	26,9%	26,9%
Bio-methane	Microalgae	15,4%	19,2%	65,4%

South.

9. The biofuel experts who were consulted work in the field of academic research, research and development, consulting and the biofuel industry.

### 3.3. Validating the biofuel set

Based on a literature survey, a biofuel set was submitted for the stakeholder's review [60, 61,63,101]. By considering their cultural background and expertise, stakeholders were asked to give their points of view on each biofuel option by explaining whether they agreed, disagreed or neither agreed nor disagreed with the hypothesis of a large scale production in France by 2030 (Table 2).

First generation biofuels, also called conventional biofuels, are produced from food-crops such as rapeseed, soybean and maize. By considering the increasing concerns about ILUC and food security issues, the representatives of NGOs consider that conventional biofuels will not be part of the biofuel mix by 2030 to the benefit of advanced biofuels, i.e. biofuels produced from lignocellulosic feedstocks, wastes and non-food crops. From the perspective of other stakeholder groups, conventional biofuels will still be the most produced in France by 2030.

Depending on the feedstock, Hydrotreated Vegetable Oil (HVO) can be defined as conventional (rapeseed and palm oils) or advanced biofuel (waste oil) based on the potential competition with food. In either case, stakeholders have highlighted their high production costs and consequently HVO deployment will depend on the European support scheme through "double counting policy", i.e. a legal mechanism that allows advanced biofuels to count twice towards European

incorporation objectives. Opinions about the double counting mechanism are split depending on the stakeholder group: NGOs and government point out a higher support for advanced biofuels through the incentives for refining industry and fuel distribution, whereas feedstock and biofuel producers report there is an unfair competition.

From the overall stakeholder perspective, second generation biofuels, i.e. biofuels produced from lignocellulosic feedstocks, will be produced on a large scale by 2030. However, stakeholders have expressed several reserves about the availability of sustainable feedstock: biomass availability from energy crops is limited by land-use issues [96] and also by feedstock usage competition such as methanisation [2]. Moreover, the collect of residues is limited by environmental sustainability concerns, i.e. preventing erosion, soil carbon loss and nutrients [105].

Third generation defines biofuels produced from photosynthetic micro-organisms such as microalgae. Opinions about microalgae biomass availability for energy-uses are split: based on the opinions of 55 worldwide microalgae experts [101], microalgae biofuels will most probably reach a fully commercial scale between 2021 and 2030 while representing from 5% to 10% of the worldwide fuel consumption. According to Ademe [2], because of the early stage of development, microalgae will not be part of the biofuel feedstock mix by 2030. According to most of the stakeholders, microalgae biofuels are considered as highly promising but opinions were split concerning the time horizon ranging in between 2030 and 2050. European and French fuel consumption in the transport sector is balanced in favor of diesel [112]. Consequently, only the hypothesis of large scale deployment for the biodiesel option was supported by more than 50% of the respondents. Finally, large scale deployment of biogas options in the transport sector were considered irrelevant by almost all the stakeholders because of end-user acceptability and much better efficiency through heating and power generation than liquid fuel production.

### 3.4. Validating sustainability criteria and its associated indicator set

Based on literature survey, a non-exhaustive list of sustainability criteria were submitted to stakeholder review [104,112,118,126,33,48,80]. By considering their own group concerns regardless of others, stakeholders were asked to give their point of view about the most relevant biofuel sustainability criteria. In other words, the perspectives of stakeholders were captured without aiming to reach a consensus about biofuel sustainability criteria but rather by considering the specificities of each heterogeneous stakeholder group [25,51]. Presented in Table 3, stakeholder criteria for biofuel sustainability are split between economic (45%), environmental (29%) and social considerations (26%).

As mentioned by Buchholz et al. [21], stakeholder consensus about sustainability criteria is very low among the different professions represented. In the present study, only 5 of the 22 sustainability criteria were identified with a consensus higher than 50%, namely the GHG mitigation, the ILUC impact, the biofuel production cost, the additional costs for end-users and the air quality. Such a result highlights the completeness requirement as one of the keystones of the sustainability assessment.

Although some sustainability criteria can be characterized by a unique dimension such as GHG emission, other criteria cannot be. For example, biofuel producer concern for biomass availability relies on legal aspects through land-use limitation and thus land productivity in order to limit food security, soil erosion and ILUC impacts, i.e. socio-environmental aspects. For each criterion, stakeholders express their concerns about biofuel sustainability that needs to be assessed through adequate measurement scales. Consequently, the indicator set cannot be separated from the sustainability criteria set for meeting the acceptance requirements of stakeholders [38].

**Table 3**  
Sustainability criteria identified by the stakeholders.

Sustainability criteria	Consensus (%)	Stakeholder groups <sup>a</sup>	Economic concerns	Social concerns	Environmental concerns
GHG mitigation	100,0%	1,2,3,4,5,6,7,8			x
ILUC	75,0%	3,4,5,6,7,8			x
Biofuel production cost	75,0%	2,3,4,5,6,7	x		
Additional cost for end-users	50,0%	4,5,6,7	x	x	
Air quality	50,0%	4,5,6,7			x
Renewable energy ratio	37,5%	4,5,6			x
Land productivity - Energy yield	25,0%	1,7	x		
Land productivity - Protein yield	25,0%	1,7	x		
Food security	25,0%	7,8		x	
Eutrophication	25,0%	1,8			x
Water footprint	25,0%	1,8			x
Job creation	25,0%	1,7	x	x	
Biomass availability	12,5%	2		x	x
Biofuel availability	12,5%	4		x	x
Incomes from feedstock	12,5%	1	x		
Biofuel international competition	12,5%	2	x	x	x
Market opportunities	12,5%	1	x		
Biofuel incorporation costs	12,5%	3	x		
Existing logistics (fuel distributors)	12,5%	4	x		
Overconsumption	12,5%	5	x	x	
Budget impact	12,5%	7	x		
Transparency	12,5%	8		x	
Repartition			45%	29%	26%

<sup>a</sup> Stakeholder group numbers refers to Section 3.1.

#### 4. Sustainability assessment of the biofuel set

The sustainability criteria set is associated with an indicator set in order to measure the performances of biofuel options, i.e. their capacity to fulfill each of the stakeholder criteria. The sustainability assessment of the biofuel set requires addressing multiple criteria characterized by a heterogeneous level of uncertainty, but also different time frames [49]. Moreover, the evolving socio-economic and legal context can also impact several criteria such as biomass availability through land-use restriction as mentioned previously. Consequently, the next section presents a range of possible biofuel performances ranging between optimistic and pessimistic values and continuing through explicit measurement methods with regards to transparency and stakeholder acceptance considerations [38,73].

##### 4.1. Economic indicator set

Economic considerations focus on biofuel market opportunities, including incorporation mandates, biofuel competitiveness, coproduction opportunities and the feedstock availability. NGOs are the only stakeholder group which does not consider any economic sustainability criteria.

##### 4.1.1. Biomass and biofuel availability

Through the security of supply, biomass availability is a critical sustainability criterion for biofuel producers and fuel distributors. Biomass availability relies on both legal and social considerations: through food security issues, importation limitation and agricultural sector support for food crop based biofuels [2]; through competition for different energy valorization for second generation biofuels feedstocks [2]; and through site characteristics for microalgae biofuels [58] such as climate, gradient and CO<sub>2</sub> availability, i.e. the proximity to industries that generate high volumes of CO<sub>2</sub>. Based on the expected land availability and productivity by 2030 (Table 4), Table 5 presents both biomass and biofuel availability.

On the one hand, Table 4 presents the expected biomass productivity per feedstock by 2030 [15,30,60,105]. On the other hand, based on both biomass energy content and process yields [110,30,36], Table 4 presents the expected biofuel land productivity by 2030. Food crop based biodiesels are assumed to be produced through

**Table 4**  
Expected land productivity by 2030.

Scenario	Biomass (ton per hectare)		Biofuel (toe per hectare)	
	Pessimistic	Optimistic	Pessimistic	Optimistic
Wheat ethanol	7,95	9,51	1,44	1,72
Maize ethanol	11,13	13,62	2,66	3,25
Sugar beet ethanol	12,04	13,94	6,21	7,19
Sugar cane ethanol	8,97	9,31	4,63	4,80
LC ethanol <sup>a</sup> (agricultural residues)	10,00	12,00	1,28	1,54
LC ethanol (forestry residues)	8,00	18,00	1,04	2,35
LC ethanol (energy crops)	13,00	20,00	1,67	2,57
Rapeseed biodiesel	4,06	4,59	1,53	1,73
Soybean biodiesel	3,09	3,50	0,53	0,60
Palm biodiesel	5,31	5,54	4,46	4,65
HVO (rapeseed)	4,06	4,59	1,50	1,70
HVO (palm)	5,31	5,54	4,46	4,65
BtL <sup>b</sup> biodiesel (agricultural residues)	10,00	12,00	1,71	2,05
BtL biodiesel (forestry residues)	8,00	18,00	1,39	3,13
BtL biodiesel (energy crops)	13,00	20,00	2,23	3,42
Microalgae biodiesel (raceway)	20,00	50,00	4,51	11,27
Microalgae biodiesel (PBR)	40,00	60,00	9,02	13,53

<sup>a</sup> LC: lignocellulosic.

<sup>b</sup> BtL: Biomass to Liquid.

transesterification with a typical mass yield of 97% for FAMES and 80% for HVOs [36,110].

Lignocellulosic (LC) ethanols are assumed to be produced through a biochemical pathway with a typical mass yield of 30% when Biomass to Liquid (BtL) biodiesels are assumed to be produced through a thermochemical pathway with a typical mass yield of 40% [3]. For both agricultural and forestry residues, the collection rate is assumed to

**Table 5**

Expected biomass (and biofuel) availability in France by 2030 (ktoe).

Biomass / Biofuel Scenario	Biomass (kton)		Biofuel (ktoe)	
	Pessimistic	Optimistic	Pessimistic	Optimistic
Imported biofuels	–	–	1050	1050
Wheat ethanol	2202	2634	398	476
Maize ethanol	3084	3772	736	900
Sugar beet ethanol	26038	30146	1344	1556
LC ethanol (agricultural residues)	5329	11872	684	1524
LC ethanol (forestry residues)	6500	9170	848	1197
LC ethanol (energy crops)	2300	12000	295	1541
Rapeseed biodiesel	6245	7063	2356	2665
BtL biodiesel (agricultural residues)	5329	11872	912	2032
BtL biodiesel (forestry residues)	6500	9170	1131	1596
BtL biodiesel (energy crops)	2300	12000	394	2054
Microalgae biodiesel (raceway)	2966	7416	669	1672
Microalgae biodiesel (PBR)	9994	14991	2253	3379

be limited for preventing the risks of erosion, soil carbon loss and nutrients. By considering land slope and climate and soil characteristics in France, Searle and Malins [105] considered biomass retention constraints of 80% for forestry residues while Ademe [3] recommended 67% for agricultural residues. Forestry residue availability also depends on both the wine and wood industries which allow higher biomass availability without increasing land requirement.

Data about microalgae biomass productivity is based on expert consultation whereas data about the lipid content, the efficiency of lipid extraction and transesterification are based on Subhadra and Edwards [14]. Two different production pathways are considered, through raceways and photobioreactors (PBR) [28]. By considering social, environmental, economic, legal and technical constraints, Table 5 presents the expected biomass and biofuel availability in France by 2030.

Table 5 provides the biofuel availability that relies on the land availability [2,24] and the expected yield by 2030 [15,36,60]. Based on Ademe [2], land dedicated to food crop biofuels production will be limited to the level of 2010 with regards to food security concerns, i.e. 1, 677 kha split between 1, 450 kha for biodiesel and 277 kha for ethanol [24]. Expected yield improvement may imply a potential of 3 Mtoe by 2030 compared to 2.5 Mtoe in 2010 by considering equivalent feedstock mix. However, the land allocation for different feedstocks could also depend on policy arbitrage by 2030. Through sustainability concerns such as GHG, ILUC and food security, both biomass and biofuel availability related to imported biofuels are expected to be limited for all types of feedstocks at an overall level of 1 Mtoe [2].

Concerning biofuels produced from agricultural and forestry residues, biomass availability depends on both environmental and legal considerations. From the feedstock and biofuel producer points of view, competition between the different energy-uses of biomass resource might hamper their security of supply [30]. Biofuel producers and academic experts have even pointed out the risk of fossil energy-use such as coal and petroleum coke, in order to ensure that biofuel production units run at full capacity and to ensure their economic viability. For environmental sustainability concerns, the availability of residues is limited by retention rates but also by feedstock use competition, namely livestock feeds, mushroom cultivation, horticulture for agricultural residues and other energy uses for agricultural and forestry residues [3,105]. Consequently, Table 5 presents the biomass availability for energy-usage ranging from optimistic to pessimistic values depending on whether biofuel, heat, biogas and electricity is considered the relative higher priority [2,105].

**Table 6**

Expected income from feedstock by 2030 (€ per ton).

Feedstock	Pessimistic	Optimistic
Imported feedstocks/biofuels*	- €	- €
Wheat	11 €	79 €
Maize	- €	58 €
Sugar beet	11 €	12 €
Rapeseed	327 €	707 €
Agricultural residues	90 €	108 €
Forestry residues	42 €	117 €
Energy crops	104 €	85 €
Microalgae biodiesel (raceway)	- 184 €	- 1 304 €
Microalgae biodiesel (PBR)	- 1 500 €	- 3 800 €

\* Imported feedstocks/biofuels generate incomes from feedstock abroad but none in France.

Microalgae biomass availability rely on land availability which depends on economic, social, environmental, technical and legal constraints such as slope gradient, land-use, and climate characteristics. Finally, between 0.27% and 0.45% of French lands are adequate for deploying microalgae for biofuel production [58]. Consequently, depending on the technology and regardless of economic considerations, biomass availability for microalgae could reach from 2.2 to 3.4 Mtoe.

#### 4.1.2. Market opportunities

Relying on the set aside policy, France has started to support biofuel deployment for creating new market opportunities for the agro-food industry while hedging its exposure to risks related to international competition through market diversification (Table 6).

Food crop based feedstock price assessment depends on land productivity [36], expected yield improvement [15,30,61,98], oil price scenarios [61] and both commodity prices and prospective production costs [30,35,59,72,120].

Unlike food crop feedstocks, there is currently no global market for residues and there is a high degree of uncertainty concerning the cost curve for residues [50]. The expected incomes for residues were assessed through both the expected biomass price by 2030 [30,61] and the residue collection costs [72]. Focusing on the third generation, valorizing microalgae as biofuel implies moving from a high value niche market toward a low value but large market one [58].

Based on expert consultation, reaching the biofuel market implies lowering the microalgae biomass production costs to around a threshold of € 1000 per ton while the production cost is generally expected to be higher [28,98]. Based on Delrue et al. [28] and regardless of the valorization of byproducts, biomass production costs are assumed to respectively represent 76% and 93% of the overall biofuel production costs for raceway and PBR (including operating, cultivation, harvesting and drying costs). The biorefinery approach allows for the valorization of by-products and thus higher incomes, especially for microalgae feedstocks [123]. For example, the price of omega-3 fatty acids (O3FA) exceeds \$100, 000 per ton but large-scale deployment of microalgae biofuels may quickly saturate the high-value product markets [14]. Indeed, the O3FA market currently represents between 0.2 and 0.4Mton compared with 100Mton for the biofuel one [14,93]. Market diversification is also an opportunity to lower the risks related to international competition (Table 7):

Depending on both biofuel feedstock and production processes, biofuel production allows for the valorization of different byproducts [14,61]. Food crop and microalgae based biofuels allow the production of food and feed coproducts, namely dried distillers' grain with solubles (DDGS) for cereal based ethanol; respectively bagasse and pulp for sugar cane and sugar beet ethanol and protein meals for biodiesels [61]. CO<sub>2</sub> for food-use can also be generated through the production process of both sugar and lignocellulosic based ethanol [5]. Both food crop and microalgae based oils require an esterification process which

**Table 7**  
Main market opportunities / market diversification criterion.

Feedstocks	Biofuels	Feed	Food	Chemical	Energy
Wheat	Ethanol	x	x		x
Maize	Ethanol	x	x		x
Sugar beet	Ethanol	x	x		x
Sugar cane*	Ethanol	x	x		x
Rapeseed	Biodiesel	x		x	x
Soybean*	Biodiesel	x		x	x
Palm*	Biodiesel	x		x	x
HVO* (rapeseed/palm)	Biodiesel	x			x
HVO* (waste oil)	Biodiesel				x
Agricultural residues	Both		x		x
Forestry residues	Both		x		x
Energy crops	Both		x		x
Microalgae	Biodiesel	x	x	x	x

\* Imported biofuels.

generates glycerin for chemical markets [59].

Second generation biofuels production processes generate bio-wastes such as fibers and lignin that can be valorized in energy through electricity, heat and biogas generation. HVO produced from food crop based oils allows feed by-products valorization upstream contrary to waste oil feedstock. Unlike biofuels produced through the transesterification process, the HVO process generates liquefied petroleum gas which is valorized on site to meet heat and energy requirements [1]. Although Table 7 presents the main market diversification opportunities for coproducts valorization, other possibilities exist such as cosmetic and medicine markets for microalgae biodiesel [124]. Focusing on BtL biodiesel and by assuming additional costs, naphtha can be generated through an additional refining process but the potential of the naphtha market is highly uncertain [30].

#### 4.1.3. Competitiveness of biofuels

Through the consideration of competitiveness, biofuels production cost compared with oil based fuels represents the main economic concern for all stakeholder groups, with the exception of NGOs which focus on socio-environmental criteria. From the perspective of biofuel producers, French biofuel production has to be competitive compared with fossil based fuels but also with imported biofuels. Consequently, promoting international fair competition requires preventing potential social and environmental dumping through legal measures. In order to assess the additional shipping costs of imported biofuels (adapted from MCRIT [84] and Wolfgang, [119]), sugar cane ethanol, soybean and palm are respectively assumed to be produced in Brazil, Argentina and Indonesia; transported by water to Rotterdam and finally delivered in France by road. Based on both freight cost trends [119] and biofuel/feedstock origin, additional costs for imported biofuels range from €0.02 to €0.137 per liter. The refining industry, fuel distributors, end-

users and car manufacturers focus on biofuel costs compared with those of oil based fuels which rely on expected crude oil prices [60] and French refining costs (adapted from both UFIP [113] and expert consultation).

Fig. 1 presents the expected biofuel costs in France by 2030. Regardless of socio-environmental concerns, both gasoline and diesel fuels should be competitive by 2030 with an expected price ranging from €0.32 to €1.11/lge (i.e. from \$50 to \$180 per barrel). Sugarcane ethanol imported from Brazil is the most competitive biofuel, followed by the other food crop based ethanols and second generation biofuels. Food crop based biodiesels require higher oil prices to be competitive with an average cost of €0.85/lge. Expected demand for palm oil for both food and energy uses is expected to rise by 2030 which should hamper palm based biodiesels relative competitiveness compared with other food crop based biodiesels. Finally, by assuming a large scale deployment, microalgae biodiesel should reach costs ranging from €1.34 to €4.47/lde depending on the process pathway [28]. Technological and biological breakthroughs are needed, expected and even on-going for microalgae biofuel [56].

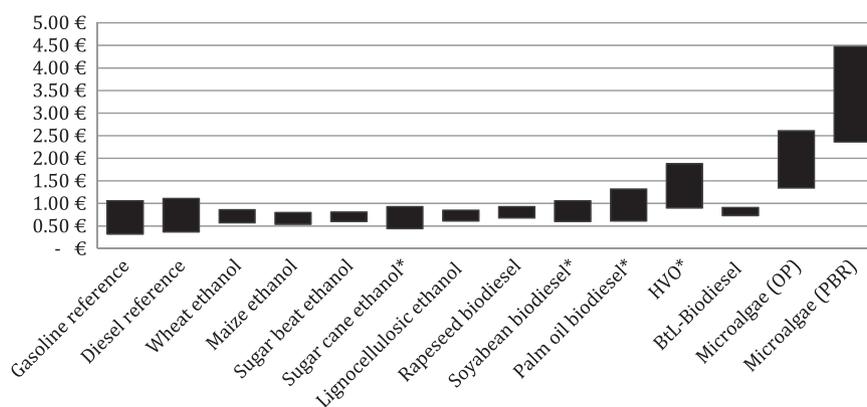
Biofuel competitiveness is also about logistics for the refining industry and fuel distributors. Considering that the French fuel consumption in the transport sector is balanced in favor of diesel [113], refiners have to import diesel and export gasoline. Consequently, biodiesel importation allows refiners to reduce the amount of diesel importation and thus freight costs (\$15/ton). Ethanol incorporation implies higher gasoline exportation which generates additional freight costs (\$20/ton). Moreover, an additional cost is also induced by the lack of competitiveness of French refineries compared to European ones [34,113]. From a fuel distributor's point of view, biofuel incorporation could imply the development of the range of fuels which means additional costs through pumps, tanks and logistics. Based on Turckin et al. [112], costs for additional pumps range from €16 000 for liquid fuels to €250 000 for natural gas fuels.

#### 4.2. Social indicator set

Government and feedstock producer social sustainability criteria are partly linked to economic concerns for fuel poverty and job creation whereas NGOs mainly focus on food security issues regardless of any economic considerations. Transparency about feedstock origin was also mentioned by NGOs. Based on France AgriMer and Biomass Biofuels Sustainability Association (2BS), waste oil is currently the only feedstock that is not clearly and easily traceable, especially imported waste oil based biofuels.

##### 4.2.1. Food security

From the government and NGOs points of view, threats to food security can eventually hamper biofuels social sustainability through food price increases. Literature provides a wide variety of studies that



**Fig. 1.** Range of expected biofuel costs in France by 2030 (€/lde, €/lge). \*Imported biofuels.

**Table 8**  
Arable land requirement per energy produced (ha per toe).

Biomass / Biofuel	Arable land requirement (hectare per toe)		Feed-byproduct yield (ton per hectare)	
	Pessimistic	Optimistic	Pessimistic	Optimistic
Wheat ethanol	0,70	0,58	2,39	2,85
Maize ethanol	0,38	0,31	4,12	5,04
Sugar beet ethanol	0,21	0,18	4,70	5,44
Sugar cane ethanol	0,27	0,26	13,33	13,84
LC ethanol (agricultural residues)	0,00	0,00	0,00	0,00
LC ethanol (forestry residues)	0,00	0,00	0,00	0,00
LC ethanol (energy crops)	0,60	0,39	0,00	0,00
Rapeseed oil	0,65	0,58	1,95	2,20
Soybean	1,88	1,67	2,41	2,73
Palm oil	0,22	0,22	0,59	0,62
HVO (rapeseed)	0,67	0,59	1,95	2,20
HVO (palm)	0,22	0,22	0,59	0,62
BtL biodiesel (agricultural residues)	0,00	0,00	0,00	0,00
BtL biodiesel (forestry residues)	0,00	0,00	0,00	0,00
BtL biodiesel (energy crops)	0,45	0,29	0,00	0,00
Microalgae biodiesel (raceway)	0,22	0,09	12,00	30,00
Microalgae biodiesel (PBR)	0,00	0,00	24,00	36,00

assess the impacts of biofuel in both food supply and prices (for a review, see Serra and Zilberman, [107]). According to Mueller et al. [88], literature provides assessment of the biofuel contribution in increasing food prices that ranges from 3% to 75%. From perspectives of biofuel and feedstock producers, food security impact is limited by feed byproducts. In the present paper, considering the uncertainty about biofuel impact on food security and with regards to stakeholder perspectives, the food security criterion is assessed through land requirement that competes with food production. In other words, the lower the land requirement, the lower the risk to food security.

Table 8 presents the arable land requirement to produce a ton of oil equivalent (toe) depending on the crop yield [15,36,60] and processes yields [14,30,36] expected by 2030. Ethanol biofuels have better yield and thus lower impacts on land requirement than biodiesels (Table 8). The most land-intensive biofuel is soybean biodiesel that requires from 3 to 10 times more surface compared with other food crop based

biofuels at equivalent energy content. From the point of view of feedstock producers, domestic feed by-products particularly limit food security impact by the substitution of imported soybean by rapeseed meals which have lower socio-environmental impacts while generating employment in France (nearly 1.6 of direct job creation per kton according to Raes et al. [99]). Moreover, biofuels by-products for feed usage allow a higher protein independence which is considered as sustainability criterion by feedstock producers and the government. Biofuels produced from residues, waste oil and microalgae do not require feedstocks that compete with food, thus their impact on food security is considered null.

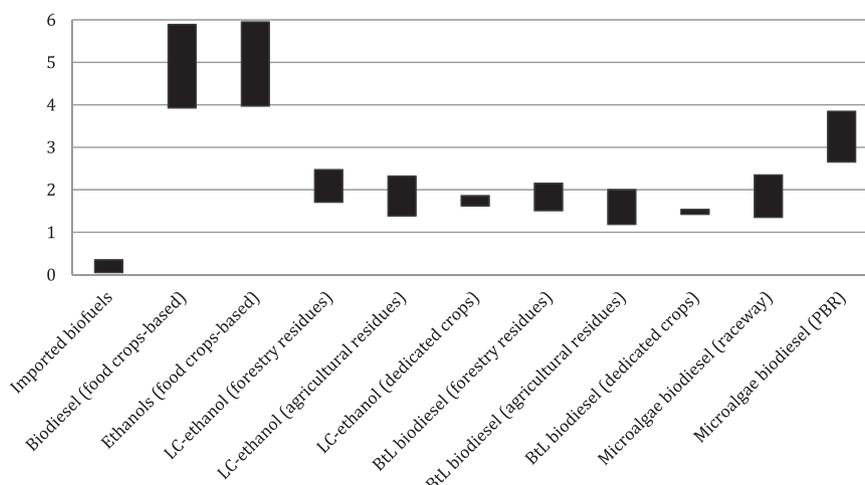
#### 4.2.2. Direct job creation

From feedstock producers and government perspective, job creation through biofuel deployment is a key sustainability criterion. Based on Raes et al. [99] and expert consultation, direct job creation relies on the fertilizer and seed industry; feedstock production, transport and storage; biofuel production, transport and storage.

Fig. 2 presents the potential job creation per type of biofuel in France by 2030. For imported biofuels, employment ranges from 0.05 to 0.35 jobs per kton depending on whether biofuel (transport related job) and feedstock is imported (transport and processing operation related jobs). Land availability for first generation biofuel production by 2030 is expected to be legally limited to the 2010 level for socio-environmental concerns [2]. Based on expert consultation, with respect to a 20% margin of error, job creation related to first generation biofuel production is assumed to be constant, i.e. nearly 5 jobs per thousand tons. Food crop biofuels are intensive in agricultural jobs which represent more than 85% of the overall employment [99].

Job creation related to LC-ethanol and BtL biodiesel depends on employment related to feedstock production and collection, biorefinery processing jobs [105] and biofuel storage and transportation [99]. Based on Searle and Malins [105], feedstock production and collection should employ between 0.85 and 1.70 jobs per thousand tons depending on the feedstock, i.e. energy crops, agricultural and forestry residues; operational processing should generate from 30 to 48 jobs per biorefinery. Job creation related to biofuel transport and storage are assumed to be the same for advanced and conventional biofuels. Although construction should represent 600 jobs per facility, they are not included in Fig. 2 because they are not permanent, lasting only 2 years [105].

PBR facilities are expected to generate 43 jobs for 1 000 ha whereas raceway facilities should generate from 10 to 13 jobs for 100 ha [64,77]. Based on expert consultation, the esterification process of microalgae oil is assumed to generate as many jobs per kilo ton as food crop based oil, i.e. 0.22 jobs per kilo ton [99]. According to the Algae



**Fig. 2.** Potential job creation related to biofuel production (job per kt).

Biomass Association, the construction phase should respectively represent 2000 and 600 non-permanent jobs for PBR and raceway facilities. According to Bio-era [13], the research and development sector associated with the deployment of advanced biofuels may account for 3% of the overall job creation. Considering the lack of available data for France, Fig. 2 does not include either construction or research and development jobs.

#### 4.2.3. Fuel-poverty and government budget

Fuel poverty is defined when household budget spending is higher than 8% for heat, including domestic hot water, and 4.5% for transport. In 2015, around 22% of French households were in fuel poverty [23]. Consequently, additional costs for end-users implied by biofuel deployment are important to fuel distributors, the government and obviously end-users. Additional costs for end-users can be characterized by the relative competitiveness of biofuels and fossil fuels, including over-consumption, car purchasing price, biofuel and fuel taxes. Based on consultation with car manufacturers, additional costs for high blending engines are very low for ethanol options which require less than €100 per car for flex-fuel technology. By considering a slightly higher cost because of a more regular maintenance, French diesel engines already allow a blending rate up to 30%. However, according to car manufacturers, neither biofuel policy nor the demand of end users currently justifies a deployment of high blending engines such as flex-fuel cars.

From the point of view of the government, the budget impact relies on revenues and spending, i.e. tax revenues and subsidies to support the biofuel deployment. In the present section, the budget spending is assumed to cover the additional cost for end-users for fuel poverty concerns. The budget impact has been assessed through the average tax revenues generated from job creation [97,105], TICPE and VAT (Value Added Tax) surplus while considering both low and high oil price scenarios [61]. TICPE is applied with regard to energy volume, considering both ethanol and biodiesel lower energy contents compared with oil based-fuels [30,4,98] and the tax surplus is mechanically generated at equivalent energy consumption. Moreover, regardless of tax exemption, the higher the biofuel cost compared with oil based fuels, the higher the VAT revenues.

Table 9 presents the additional cost for end-users implied by a 10% blend of biofuel and the overall budget impact for government. A low-price oil scenario implies an additional cost for end-users ranging from €0.03 to €0.06 per liter (except for microalgae). Considering new tax revenues generated from TICPE, VAT and professional taxes, the overall budget impact is positive for the biofuel options that are

**Table 9**

Additional cost for consumers (€/T) and overall government budget impact (c€/lde, c€/lge).

Indicators	Cost for end-users		Budget impact	
	(c€ per lde/lge)		(c€ per lde/lge)	
Oil price scenario	50\$ per barrel	180\$ per barrel	50\$ per barrel	180\$ per barrel
Wheat ethanol	0,04 €	-0,02 €	0,09 €	0,14 €
Maize ethanol	0,03 €	-0,03 €	0,10 €	0,15 €
Sugar beet ethanol	0,03 €	-0,03 €	0,10 €	0,15 €
Sugar cane ethanol*	0,04 €	-0,01 €	-0,02 €	0,04 €
Lignocellulosic ethanol (average)	0,04 €	-0,02 €	0,10 €	0,14 €
Rapeseed biodiesel	0,04 €	-0,02 €	0,03 €	0,08 €
Soybean biodiesel*	0,03 €	-0,01 €	-0,02 €	0,01 €
Palm oil biodiesel*	0,03 €	0,03 €	-0,02 €	0,04 €
HVO*	0,06 €	0,09 €	-0,00 €	-0,03 €
BtL-biodiesel (average)	0,04 €	-0,03 €	0,01 €	0,07 €
Microalgae biodiesel (average)	0,29 €	0,18 €	-0,18 €	-0,08 €

\* Imported biofuels.

produced in France except for microalgae biodiesel because of its high expected cost. The budget impact for ethanol options is also higher compared with biodiesels because of its lower energy content which generates additional taxes. Considering a high-cost oil scenario, biofuels are more competitive compared with fossil fuels, except for HVO, palm oil and microalgae biodiesels because of their expected higher costs [28,60,63]. In this scenario, even imported biofuels allow the government budget to be positive, except for HVO and microalgae biodiesels.

#### 4.3. Environmental indicator set

Environmental sustainability of biofuels is considered by all stakeholder groups but by different criteria. From the points of view of both NGOs and feedstock producers, environmental sustainability of agriculture is a common criterion through the water footprint (Fig. 3) soil eutrophication (Table 10), and GHG emissions considerations (Fig. 4). Although direct GHG emission is the only criterion common to all stakeholder groups, opinions are split concerning ILUC impacts (Fig. 5). Car manufacturers, the government and end-users also point out air quality as an environmental sustainability criterion (Table 12).

##### 4.3.1. Environmental sustainability of agriculture

The environmental sustainability of agriculture includes water requirement [37,122] and eutrophication potential [4,59]. Based on Gerbens-Leenes and Hoekstra [45] and Gerbens-Leenes et al. [44], France is one of the most effective countries concerning the water footprint (WF). According to Berndes [12] and Gerbens-Leenes et al. [43], water requirement and evapo-transpiration will increase but especially from 2030 to 2100. Consequently, Fig. 3 presents the expected WF of biofuels in 2030 based on Gerbens-Leenes et al. [46], Bulsink (2010) [22], Wu et al. [120] and Gerbens-Leenes et al. [44].

A blue WF refers to surface and groundwater volumes consumed while a green WF refers to the rainwater consumed [43]. First generation ethanol production usually requires a lower amount of water with an average consumption of 120 m<sup>3</sup> per GJ, i.e. 2, 500 l water per liter of biofuel produced, compared with biodiesels (537 m<sup>3</sup> per GJ i.e. 16, 800 l water per liter biofuel produced). Based on Bulsnik [22], palm crops in Indonesia require the greatest amount of water because of climate issues, namely high evapo-transpiration and low effective rain falls (i.e. no green water). Advanced biofuels produced from wood, miscanthus and microalgae have the lower blue WF impact [121].

Due to fertilizer-use, large nitrogen and phosphorus-related environmental burdens are released from the soil during cultivation [71] which induce eutrophication. Eutrophication generates several negative environmental impacts such as the decrease of plant and animal biodiversity, the increase of water and soil toxicity and the increase of algae at the expense of other biomass [4].

Table 10 presents the biofuel potential of eutrophication [4,59,8]. Compared with fossil fuels, first generation biofuels have a 10–20 times higher potential of eutrophication because of fertilizer usage [4]. Advanced biofuels have a lower eutrophication potential than food-crop based biofuels but still higher than fossil fuels.

##### 4.3.2. GHG emissions

Concerns about GHG emissions are common to all the stakeholder groups. Depending on the process and the way feedstock is produced and byproducts are valorized, Fig. 4 presents the potential of GHG mitigation of different biofuel options regardless of ILUC effects [3,28,60,63].

Advanced biofuels have a higher GHG mitigation potential than conventional ones except for microalgae biodiesel which still suffers high uncertainty concerning their process and performance [26]. Maize and wheat ethanols can also have a worse GHG balance than fossil fuels (Fig. 4, based on IAE [60]) because of direct land use change issues such as deforestation. Focusing on the French context, a respective

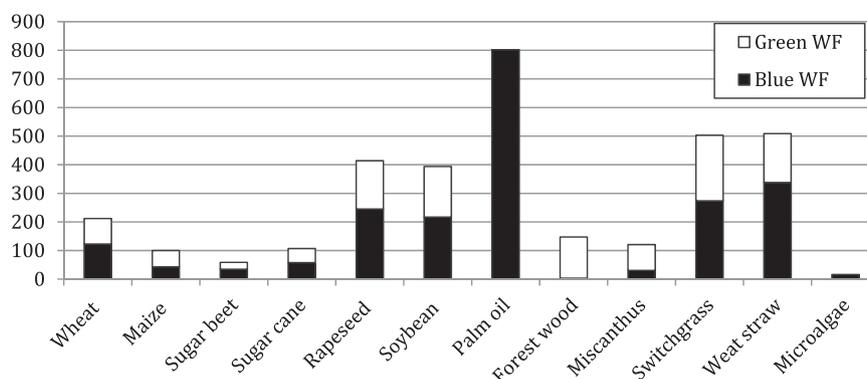


Fig. 3. Blue and green water footprints of biofuel (m<sup>3</sup> per GJ).

Table 10

Biofuels potential of eutrophication (kg PO<sub>4</sub><sup>3-</sup>/MJ).

Biofuel	Eutrophication (kg PO <sub>4</sub> <sup>3-</sup> /MJ)
Wheat ethanol	4,11E-04
Maize ethanol	3,79E-04
Sugar beet ethanol	1,95E-04
Sugar cane ethanol	2,19E-04
Lignocellulosic ethanol	8,40E-05
Rapeseed biodiesel	3,64E-04
Soybean biodiesel	1,79E-04
Palm oil biodiesel	1,84E-04
HVO	5,00E-05
BtL biodiesel	1,00E-04
Microalgae	1,21E-04

mitigation of -42% and -35% are the most probable values for maize and wheat ethanols [4]. Additional GHG emissions may stem from ILUC, especially for food and energy crop biofuels. Indeed, producing biofuels while leaving the food supply unchanged may imply turning new lands into agricultural lands. For example, turning forest that is a natural carbon sink into agricultural land may imply additional GHG release. However, the assessment of ILUC impacts is highly uncertain [27].

Fig. 5 presents the potential GHG emissions associated with ILUC impact caused by the expansion of crops that are dedicated to biofuels [27,60,63]. Biofuels based on wastes (including waste oil based HVO), residues and microalgae are assumed to have no ILUC impact as they are not competing with food and feed crops [33]. Imported biodiesels, namely soybean, palm and HVO have the greater potential for ILUC impacts because of deforestation issues [40,65]. According to Lapola et al. [74], ILUC impacts in Brazil can also exhaust the sugarcane ethanol GHG savings because of the deforestation of Amazonian forests.

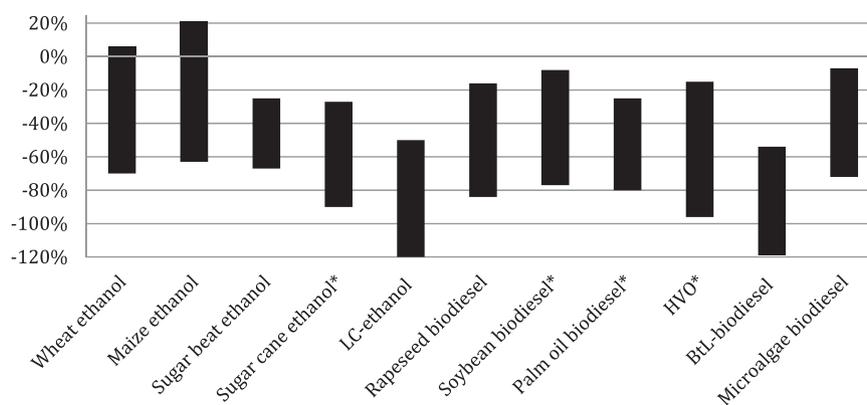


Fig. 4. Life cycle GHG balance of biofuel options (% emission reductions compared to fossil fuels). \*Imported biofuels.

#### 4.3.3. Environmental sustainability of energy consumption

Through energy independency, renewable energy consumption [8,11] and air quality criteria [108,111,79], government, end-users and car-manufacturers express their preferences for more sustainable energy consumption.

Table 11 presents the reduction of fossil energy consumption associated with the substitution of fossil based fuels by biofuels. Based on expert consultation and Ademe [4], first generation biofuels allow fossil fuel consumption reduction ranging from 34–81% for ethanol and from 59–90% for biodiesels. Despite their transport, imported biofuels have a higher renewable energy consumption ratio than first generation biofuels produced in France [4,66]. Depending on the process and byproducts valorization (see the market opportunities section), LC-ethanol and BtL-biodiesel allow a high reduction of fossil fuel consumption [10,32], of about 71% and 93% respectively. The literature provides a wide variety of studies concerning microalgae energy balance depending on the process pathways (for a review, see Quinn and Davis [98]) but based on Delrue et al. [28], the reduction of fossil fuel consumption may range between 20% and 70%.

Renewable energy consumption also allows air pollutant emissions to be reduced compared with fossil based fuels.

Table 12 presents the air quality impacts depending on biofuel type while considering different blending rates [10,32,4,86,91]. According to these studies, emission scaling factors for different blends of biofuels are only linear for low blending rates. In France, ethanol is used as an additive up to a limit of 5% in conventional gasoline, up to 10% in E10 gasoline and up to 85% in E85 for flex-fuel cars. In the present study, ethanols are produced from wheat, maize, sugar beet, sugar and lignocellulosic feedstocks. First generation biodiesel are used as diesel additives which can be blended up to 7% according to the European Committee for Standardization (8% in France since 2015). B10 assumes a 10% biodiesel blend while B100 assumes direct use of biodiesel without a fossil diesel additive. B100 is already marginally used by public captive fleets. In order to compare the different biofuels,

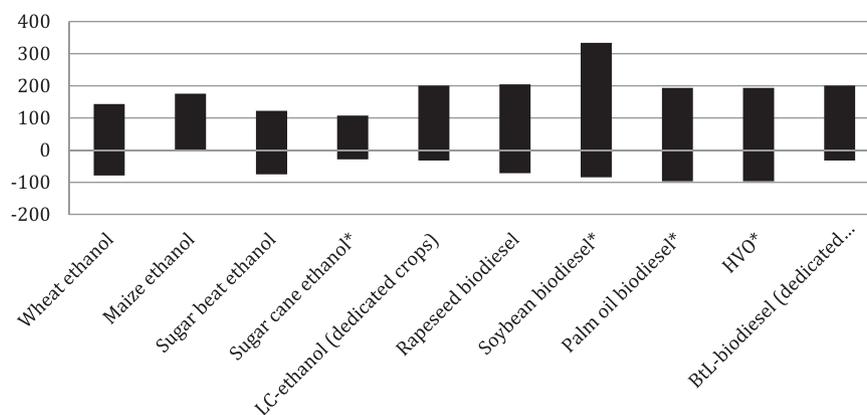


Fig. 5. Ranges of potential GHG emission associated with indirect land-use change (gCO<sub>2</sub>eq/MJ). \*Imported biofuels.

Table 11

Reduction of fossil energy consumption.

Feedstock	Pessimistic	Optimistic
Wheat ethanol	34%	42%
Maize ethanol	38%	46%
Sugar beet ethanol	37%	45%
Sugar cane ethanol	67%	81%
Lignocellulosic ethanol	68%	74%
Rapeseed biodiesel	59%	72%
Soybean biodiesel	62%	76%
Palm oil biodiesel	70%	86%
HVO	74%	90%
BtL-biodiesel	92%	94%
Microalgae biodiesel	20%	70%

Table 12

Air quality (% reduction compared with of fossil energy use).

Biofuel	HC (%)	CO	NO <sub>x</sub>	PM
Ethanol E10	-5%	-20%	0%	-40%
Ethanol E85	0%	0%	0%	-20%
Biodiesel B10	-5%	-2%	0%	-9%
Biodiesel B100	-69%	-34%	8%	-38%
HVO (10%)	-9,5%	-15,7%	-8,3%	0,7%
HVO (85%)	-27,7%	-44,0%	-12,0%	6,0%
BtL-biodiesel (100%)	-49%	-60%	2%	-16%

<sup>a</sup> HC: Hydrocarbons; CO: carbon monoxide; NO<sub>x</sub>: oxides of nitrogen; PM: particulate matter.

Table 12 considers a 10% biofuel blend. Ethanol allows a greater improvement of air quality compared with biodiesel with the exception of HVO.

#### 4.3.4. The Biofuel image from end-user perspective

From the perspectives of fuel distributors and car manufacturers, the green image of biofuel concerning the end-users viewpoints is a critical criterion. Green image is assumed to include GHG emissions, ILUC, renewable energy consumption and the air quality impact [85]. Moreover, engine compatibility and overconsumption implied by the difference of energy content compared to fossil fuels were highlighted (Table 13, based on Ademe [4], and Gehrer et al. [42]).

Ethanol represents 62% of the energy content of the gasoline reference which induces overconsumption in volume. For example, E10 implies nearly 5% of overconsumption. First generation biodiesels and microalgae biodiesel energy content are close to diesel reference (88%). For example, a 10% blend of biodiesel implies a slight overconsumption of nearly 1.5%. On the other hand, HVO and BtL biodiesels energy content are higher than the references of fossil-fuels which allow the consumption in volume to be reduced.

Table 13

Biofuel energy content (MJ/kg).

Biofuel	Energy Content
Unit	MJ/kg
Gasoline reference	43,1
Diesel reference	42,8
Ethanol	26,90
Biodiesel	37,50
HVO	44,00
BtL biodiesel	42,50

## 5. Conclusion and discussions

Sustainable biofuel deployment is characterized by a diversity of complex and conflicting values at stake associated with high uncertainties [25,115]. Based on the 5 pillars sustainability concept [92], i.e. social, economic, environmental, legal and cultural pillars, the present study proposes to assess the sustainability of several biofuel options for France by 2030 through a stakeholder-driven approach. Based on the methodology proposed by Munda, [89], 34 stakeholder representatives were identified and interviewed, including feedstock producers, biofuel producers, the refining industry, fuel distributors, car manufacturers, end-users, the government and NGOs which has led to identify sets of 22 sustainability criteria and 17 biofuel options. As mentioned by Buchholz et al. [21], stakeholder consensus concerning sustainability criteria is very low among the different professions. Indeed, only 5 of the 22 sustainability criteria were identified with a consensus greater than 50%. Consequently, the study highlights the importance of including all the stakeholder groups who have an interest, financial and otherwise, in the sustainability assessment process. Moreover, the involvement of stakeholders in the identification of other groups is critical and it has led us to identify a new group which was not mentioned in other biofuel sustainability studies [112,115,21], namely the refining industry.

Based on the average data regardless of the overlaps induced by the uncertainty, Table 14 presents the ranking of the biofuel options according to their expected performance by 2030 for each sustainability criterion identified by the French stakeholders. Biofuels are ranked from 1 to 18 with 1 being the most suited to fulfill a criterion and 18 the least which allows for the identification of the strengths and the weaknesses of each biofuel. When options equally contribute to a criterion, the same ranking was assigned. For example, wheat and maize ethanol have the potential to contribute equally to job creation.

As an illustration, let us consider biodiesel produced from microalgae through the PBR process. Based on Table 14, microalgae biodiesel is the option that contributes least to meeting the stakeholders' economic criteria because of a high production cost. Moreover,

**Table 14**  
Ranking of the different biofuel options per sustainability criteria.

Biofuels	Food crop ethanol			Lignocellulosic ethanol			Food crop biodiesel			HVOs			BTL biodiesels			Algae biodiesels		
	Wheat	Maize	S. beet	S. cane	A. residue	F. residue	E. crops	Rape-seed	Soybean	Palm	Rape-seed	Palm	Waste oil	A. residue	F. residue	E. crops	Raceway	PBR
Feedstocks																		
Land productivity - Energy yield	15	7	3	4	16	12	10	13	17	6	14	5	-	11	9	8	2	1
Land productivity - Protein yield	4	3	7	6	9	9	9	5	4	8	5	8	9	9	9	9	2	1
Biomass availability	9	8	7	10	2	3	1	5	10	10	10	10	10	2	3	1	6	1
Biofuel availability	12	11	3	13	8	9	10	2	13	13	13	13	13	4	5	6	7	1
Incomes from feedstock	6	5	7	8	2	3	4	1	8	8	1	8	8	2	3	4	9	10
Market diversification / opportunities	2	2	2	2	3	3	3	2	2	2	3	3	4	3	3	3	1	1
Incorporation costs	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1
Biofuel production cost	4	2	3	1	5	5	5	6	8	9	10	10	10	7	7	7	11	12
International competition	6	4	5	2	7	7	7	1	2	8	9	9	9	3	3	3	10	11
Existing logistics (fuel distributors)	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	2	2
Overconsumption	4	4	4	4	4	4	4	3	3	3	2	2	2	1	1	1	3	3
Food security	9	4	2	3	1	1	6	7	10	2	8	2	1	1	1	5	1	1
Job creation	1	1	1	10	4	5	7	2	10	10	10	10	10	6	8	9	5	3
Additional cost for end-users	4	1	2	8	3	3	3	6	7	9	10	10	10	5	5	5	11	12
Budget impact	4	1	2	7	3	3	3	5	9	8	10	10	10	6	6	6	11	12
Transparency	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1
GHG mitigation	11	9	6	4	3	3	3	7	8	11	11	5	1	2	2	2	10	10
ILUC	3	8	2	4	1	1	1	7	6	9	7	9	1	1	1	5	1	1
Air quality	1	1	1	1	1	1	1	3	3	3	2	2	2	4	4	4	3	2
Renewable energy ratio	11	9	10	4	5	5	5	7	6	3	2	2	2	1	1	1	8	8
Eutrophication	13	11	8	9	2	2	2	10	5	6	12	7	1	3	3	3	4	4
Water footprint	8	5	3	6	9	7	10	12	11	13	12	13	1	9	7	10	4	2

**Table A1**

List of the stakeholders who contributed to the study.

First name	Name	Organization
Maud	ANJUERE	Direction Générale du Trésor <i>Ministry of Economy and Finances</i>
Jean-Michel	ASPAR	Synacomex <i>French association for cereals and oilseeds trading</i>
Antonio	BISPO	ADEME <i>French agency for the energy efficiency and for the environment</i>
Christophe	BLAVOT	Ecologie Industriel <i>Ecological Industry</i>
Frank	BOUHERET	BP France <i>British Petroleum France</i>
Matthieu	CALAME	Fondation pour le progrès de l'homme (fph) <i>Fondation Charles Léopold Mayer for human progress</i>
Pierre	CHASSERAY	40 millions d'automobilistes <i>French car users association</i>
Gildas	COTTEN	AGPM - Association Générale des Producteurs de Maïs <i>France's General Association of Maize Growers</i>
Luis	DA SILVA E SERRA	Association 2BSvs <i>Biomass and Biofuels sustainability voluntary scheme</i>
Sylvain	DEMOURES	SNPAA - Syndicat National des Producteurs d'Alcool Agricole <i>French syndicate of agricultural alcohol producers</i>
Valérie	DERMAUX	Ministère de l'Agriculture de l'Agroalimentaire et de la Forêt <i>Ministry of Agriculture, Agro-food and Forest</i>
Bertrand	DUFRENOY	INEOS / Esterifrance <i>INEOS / French Syndicate of biodiesel producers</i>
Bruno	GAGNEPAIN	ADEME <i>French agency for the energy efficiency and for the environment</i>
Marc	GILLMAN	Total <i>Total</i>
Kristell	GUIZOUARN	Sofiprotéol / Esterifrance <i>Sofiprotéol / French Syndicate of biodiesel producers</i>
Vivien	ISOARD	Direction Générale de l'Énergie et du Climat <i>Ministry of Ecology, Sustainable development and Energy</i>
Géry	LAGRANGE	PétroInéos <i>PétroInéos</i>
Frédéric	LANTZ	IFPEN - Institut Français du Pétrole et des énergies nouvelles <i>French Petroleum Institute</i>
Nicolas	LE BIGOT	CCFA - Comité des Constructeurs Français d'Automobiles <i>Syndicate of French car manufacturers</i>
Jack	LEGRAND	GEPEA - Génie des Procédés Environnement et Agroalimentaire <i>Research laboratory</i>
Olivier	LEPINE	Algosource <i>Algosource</i>
Tarek	MHIRI	FranceAgriMer <i>Establishment for agricultural and sea products</i>
Béatrice	PERRIER	PSA - Peugeot Citroën <i>PSA - Peugeot Citroën</i>
Stéphane	POUFFARY	Energies 2050 <i>NGO Energies 2050</i>
Jérémy	PRUVOST	GEPEA - Génie des Procédés Environnement et Agroalimentaire <i>Research laboratory</i>
Caroline	RANTIEN	ADEME <i>French agency for the energy efficiency and for the environment</i>
Caroline	RAYOL	IAR pôle de compétitivité Industrielles et Agro-Ressources <i>Pole of competitiveness for agro-ressources</i>
Ronan	ROCLE	Global Bioénergies <i>Global Bioénergies</i>
Nicolas	RIALLAND	CGB - Confédération Générale des planteurs de Betteraves <i>Agricultural syndicate for sugar beet producers</i>
Sylvain	SOURISSEAU	ADEME <i>French agency for the energy efficiency and for the environment</i>
Isabelle	SPIEGEL	PWC <i>PWC</i>
Bernard	TICOT	ONIDOL - Organization Nationale Interprofessionnelle des Graines et Fruits Oléagineux <i>French interprofessional organization for oleaginous seeds and fruits</i>
Alex	TRUCHETTO	Intermarché <i>Intermarché</i>
Hugo	VALIN	IIASA <i>International Institute for Applied Systems Analysis</i>

their potential for GHG mitigation is rather low compared to other advanced biofuels such as BTL biodiesel. However, the present study proves that sustainability is not just about GHG and economic considerations. Considering impacts associated with land requirement such as food security, ILUC and feedstock availability, microalgae biodiesel is by far the most suited option with regards to several stakeholders' sustainability criteria. For example, compared with other advanced biofuels, microalgae biodiesel allows for the production of feed byproducts which is a critical issue for the government and feedstock producers through the protein independence criterion.

Biofuel sustainability assessment requires considering a wide range

of heterogeneous opinions to cope with their multidimensional impacts. Consequently, the biofuel capacity to fulfill one specific objective cannot lead to any absolute conclusion about biofuel overall sustainability, policy efficiency and whether it has a positive or negative impact. The present study proposes assessing biofuel sustainability, criterion by criterion, but regardless of the stakeholders' priorities concerning each one. Our further research will focus on developing a participatory multi-criteria analysis to incorporate the different stakeholder perspectives and priorities while taking into account the uncertainty about biofuel sustainability.

## Annexure

See [Table A1](#).

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