Ref. Ares(2020)390081 - 22/01/2020

MACROFUELS

Horizon 2020
European Union Funding
for Research & Innovation

Sustainability Assessment

MacroFuels – Project

H2020-LCE-11-2015

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Deliverable 6.6

Work package 6

Version: Final / 10 January 2020

Deliverable No. 6.6

Project Operation Manual

Dissemination Level		
PU	Public	X
PP	Restricted to other program participants (incl. the Commission Services)	
RE	Restricted to a group specified by consortium (incl. the Commission Services)	
CO	Confidential, only for members of the consortium (incl. the Commission Services)	

Nature		
R	Report	X
O	Other	

Deliverable Details			
Due date:	31 October 2019		
Submission date:	10 January 2020		
Involved participants:	Jamal Miah	ERM	
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WP no. and title:	6 Techno-economic and sustainability assessment		
WP leader:	ERM		
Task no. and title:	6.6 Sustainability assessment		
Version/Date	Final / 10 January 2020		
Keywords:	Sustainability assessment		

Executive Summary

The MacroFuels project aims to advance the technologies for producing liquid transportation biofuels from cultivated seaweed (or macroalgae), thereby providing a sustainable solution for the provision of transportation fuels for heavy goods transport and the aviation sector.

Seaweeds are amongst the fastest growing plants in the world, producing large quantities of biomass over a short timespan. They do this without the use of fresh water, fertilizers, pesticides, and farmland, that are all needed for land-based cultivation. In order to grow, seaweed needs only carbon dioxide (CO_2), sunlight and the nutrients already present in the ocean.

To validate the benefits of the seaweed biofuel concept and, ultimately, to provide a basis for the development of incentivising policies, a sustainability assessment is an integral part of the MacroFuels project. The assessment is a multi-criteria appraisal that evaluates the impacts of seaweed-derived transport fuels with respect to the environment and society and their technical and economic viability, as well as health, safety and risk aspects of the seaweed biofuel production system.

These different pillars of sustainability are assessed in individual work tasks. In order to facilitate the integrated sustainability assessment, to ensure consistency and to allow for consolidation and overall conclusions to be drawn, it is necessary that each work task is conducted on the basis of common criteria, where this is possible and appropriate. To this end, this report:

- Defines the approach taken for the integrated sustainability assessment;
- Presents the results of an integrated sustainability assessment of the MacroFuels concept; and
- Provides options to improve the sustainability performance of the MacroFuels concept.

Approach

A bespoke sustainability assessment method was developed that combines the individual sustainability criteria into an integrated colour rating chart. The stages of the method include the following: (1) collation of indicators and results from the assessments of individual sustainability aspects; (2) benchmarking of the findings based on a rating system (e.g. double positive (++), positive (+), neutral (0), negative (–), and double negative (– –)); and (3) an overall comparison and structured discussion.

Different benchmark systems were adopted for the individual sustainability criteria that are both qualitative and quantitative, as there was insufficient information to carry out a consistent comparison with a single benchmark. These benchmark systems included: ethanol from sugar beet grown in the EU for the environmental LCA; fossil fuel for economics and health & safety; Sustainable Development Goals (SDG), and EU blue growth strategy; expert judgement for local environmental impacts; and expert judgement and a social hotspots database for social criteria. Whilst this plurality of benchmarks is a significant limitation of the overall assessment, it is recommended that future assessments seek to build upon the method presented in this report in developing a common benchmark across all aspects of sustainability.

Key findings

Overall, the sustainability assessment of the MacroFuels concept presented a mixed sustainability profile, with impacts ranging from very negative to very positive. The key findings are as follows.

- The results for the majority of the environmental LCA impact categories are very negative (i.e. greater than 125% of the impact of the sugar beet benchmark (Inc. land use impacts)). The major contributor is the growing equipment, accounting up to 79% of the total impact.
- The GHG footprint is significantly higher than the RED target, fossil fuel and alternative biofuel benchmarks.
- Economic aspects are generally very negative due to the early stage of the technological development (e.g. low TRL (technology readiness level)) of the concept. The economics could be significantly improved by producing multiple products that are of higher value, e.g. pharmaceutical, cosmetic and food ingredients.
- Impacts to the local environment range from highly positive to negative depending on the site location. When suitable sites are selected, the impacts to the local environment are generally positive.
- Social impacts in general and at regional and local levels are predominantly positive to very positive. However, a number of social risks remain. Most of these can be mitigated by social standards, sound practice and the involvement of civil society via co-development and dialogues.

Recommendations for future work

Whilst the mixed sustainability profile is ambiguous, it should be noted that the MacroFuels concept is at an early stage of development compared to alternative biofuels that have received many years of research, development and investment.

In order to improve the sustainability performance of the concept, recommendations for future work focus primarily on improving the GHG footprint and economics to ensure the sustainable development of the MacroFuels technology towards commercialisation. These recommendations include the following.

1) **Expand the portfolio of high-value products derived from the macroalgae biomass** – by focusing on high value compounds, e.g. pharmaceutical, cosmetics and food and feed ingredients.
2) **Improve cultivation costs –** by improving operational (e.g. cost of seaweed is the main cost contributor) and capital costs and increasing equipment lifetime.
3) **Increase seaweed yield** – by exploring other regions of Europe (e.g. Spain and Portugal) with higher potential yields.
4) **Optimise cultivation practices** – by adopting all-year round cultivation.
5) **Use less materials –** by decreasing the materials used in the grow-out unit.
6) **Increase lifetime of grow-out equipment** – by extending the lifetime of current growing equipment beyond 10 years, based on improved corrosion-resistant materials.

7) **Use recycled materials** – by increasing recycled content towards 100% which can promote a circular blue economy.
8) **Decrease enzyme use** – by reducing enzyme use during hydrolysis.
9) **Include digestate benefits** – by attributing environmental savings associated with the digestate in GHG accounting.
10) **Alternative cultivation systems** – to explore systems where iron or galvanised steel (chains) are substituted by ropes, as found in France or the Faroe Islands, which could potentially lower environmental impacts and economic costs.

Overall, such measures should be taken as part of a holistic and optimised approach that aims to minimise materials use and natural resources and to secure social licenses for large-scale seaweed production and industrialisation of rural areas.

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1 INTRODUCTION

1.1 The MacroFuels Project

The aim of the MacroFuels project is to advance the technologies for producing liquid transportation biofuels from cultivated seaweed (or macroalgae), thereby providing a sustainable solution for the provision of transport fuels. The targeted biofuels are ethanol, butanol, and furanics, suitable as liquid fuels, fuel additives or precursors thereof for use by the heavy transport sector and, potentially, by the aviation sector.

By advancing technologies and improving efficiencies along the full supply chain, MacroFuels seeks to overcome current hurdles linked to seaweed yield and seasonality. It aims to increase the supply of biomass by using advanced textile substrates and developing a crop rotation concept, to yield fermentable and convertible sugars at economical concentrations by improving pre-treatment and storage, and to optimise the fermentation and conversion of sugars resulting in improved biofuel yields.

1.2 The Sustainability Assessment of the MacroFuels Project

Seaweeds are amongst the fastest growing plants in the world, producing large quantities of biomass over a short time span. They do this without the use of fresh water, fertilizers, pesticides, and farmland, that are all needed for land-based cultivation. To grow, seaweed needs only carbon dioxide (CO_2), sunlight and the nutrients already present in the ocean. However, this does not necessarily make biofuels from seaweed sustainable.

Replacing fossil resources by biomass does not in itself guarantee a more sustainable outcome, i.e. simply because biomass is a biogenic and a renewable resource. Although it is widely held that bioenergy and bio-based products can positively affect the environment and society, for example by replacing non-renewable resources and by promoting rural development, their production and use also results inevitably in negative effects of an environmental, social and economic nature. These may include spreading of non-native species or higher environmental and economic costs due to the complexity of, and inefficiencies in, converting biomass to fuel.

Therefore, it is necessary to conduct a comprehensive sustainability assessment of seaweed-derived transport fuels, combining appraisal of performance against individual sustainability criteria, to provide a basis for the development of incentivising policies. This is especially the case with respect to the environment and society, but also with regard to their technical and economic viability and to the health, safety and risk aspects of seaweed biofuel production systems.

This assessment draws upon the detailed techno-economic, environmental, societal and ecological evaluations carried out in the project, e.g. deliverables 6.2, 6.3, 6.4 and 6.5.

The organisational subdivision of the sustainability assessment is shown in Figure 1.1. The three pillars of sustainability (environment, society and economy) are assessed in each work task, with an additional work task covering environmental (local environment) and business risks. In this report, business risks are excluded, as these are confidential and discussed more generally within the other work packages. Hence, the outputs of these tasks are integrated into an overall sustainability assessment.

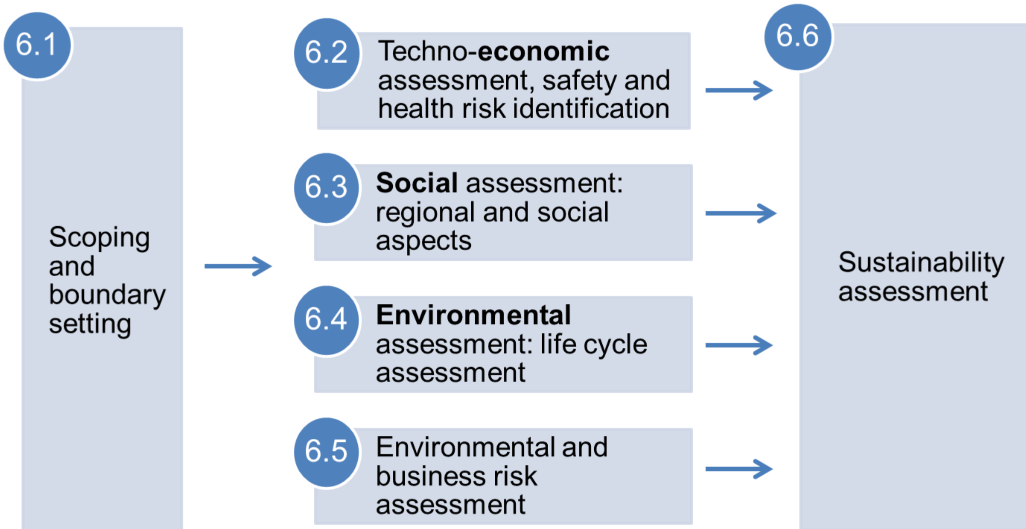

Figure 1.1 *Structure of the sustainability assessment in the MacroFuels project*

2 The MACROFUELS CONCEPT

To provide background and to set the scene for the sustainability assessment, this chapter provides a brief overview of the processes involved in generating biofuel from seaweed within the scope of the MacroFuels project.

2.1 Overview of the MacroFuels concept

The MacroFuels concept aims to progress the technologies for producing third generation biofuels from seaweed. A simplified overview of the life cycle stages involved is presented in Figure 2.1. The dashed line outlines the scope of the research conducted as part of the MacroFuels project.

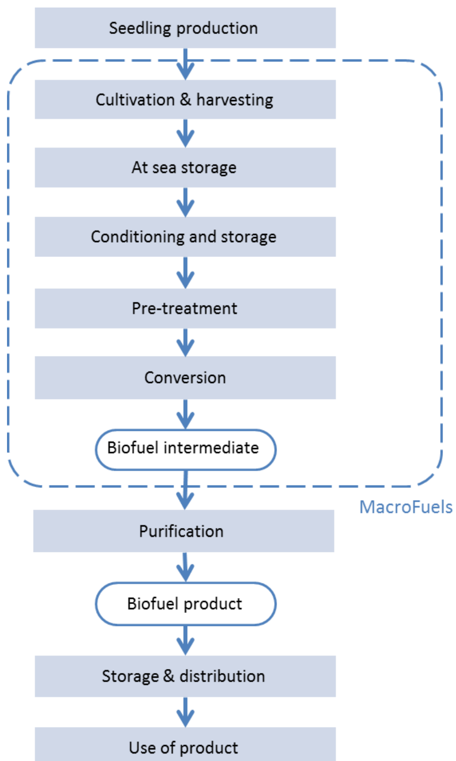

Figure 2.1 *Generic life cycle of biofuel from seaweed according to the MacroFuels concept*

The biofuels targeted as part of the MacroFuels project are ethanol (EtOH), butanol (from ABE, a mixture or acetone, butanol and ethanol), and a furanics fuel additive. The technologies employed for their production, the efficiencies achieved, and potential co-products to be used vary, depending on the value chain chosen. Within the MacroFuels project alone, the value chains can be implemented in a multitude of different variations.

2.1.1 Seedling production

Seedling cultures are produced in dedicated hatcheries. Under controlled conditions, these ensure the release of spores from fertile seaweeds, the development of the gametophyte culture, the induction of reproduction, development of juvenile sporophytes, and preparation of the juvenile sporophyte culture for application to the seaweed growth substrate.

2.1.2 Cultivation and harvesting

Following the production of seedling culture, the MacroFuels cultivation concept comprises the deployment of substrate at sea, mechanised seeding of juvenile seaweed onto substrate at sea, cultivation, and mechanised harvesting. It is important to note that the MacroFuels cultivation concept is not the cultivation system used at any of the active cultivation sites during the MacroFuels project (further details on cultivation systems and procedures used during MacroFuels, see D1.1).

The MacroFuels project considers eight different species of seaweed as primary feedstock; the objective being to evaluate their comparative suitability for cultivation. These cover four brown, three red and one green seaweed species. For the purposes of assessing the hypothetical biorefinery considered in the MacroFuels concept, the LCA study assumes that only brown seaweed (*Saccharina latissimi*) is used as feedstock in the EtOH and ABE processes and only red seaweed (*Palmaria palmate*) is used as feedstock for the furanics process. The cultivation systems and yields for both seaweeds are assumed to be the same.

The cultivation system is a two-dimensional structure, with the AlgaeNet (sheets or nets) the substrate applied in the MacroFuels cultivation concept, as shown in Figure 2.2. It allows for an optimal combination of substrate surface area for the seaweed to grow on and a density of seaweed that allows for sufficient access to sunlight and nutrient flow, as well as for mechanised seeding and harvesting. The nets will be deployed in the sea at a certain depth, with the necessary support structure of ropes, buoys and anchorage.

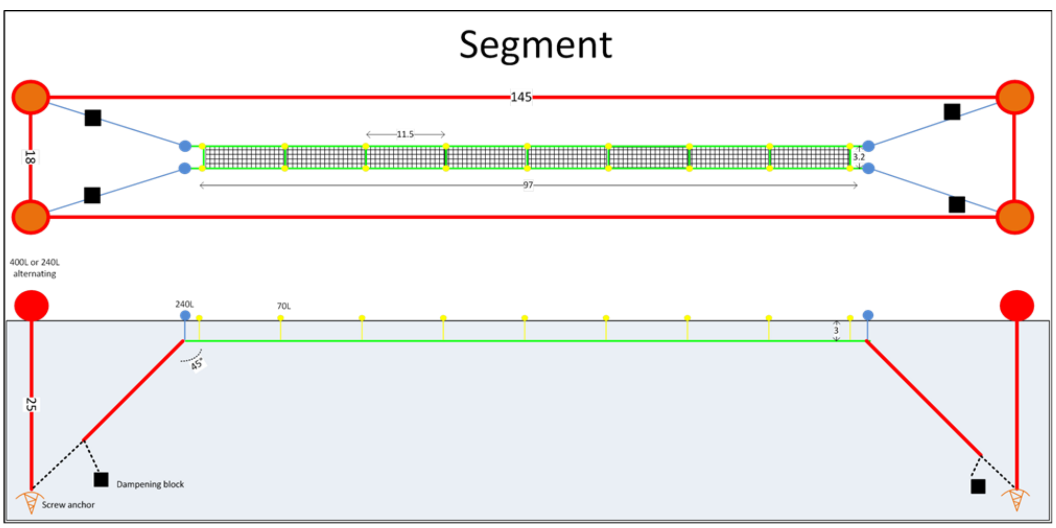

***Figure 2.2** Design of the segments of the grow-out cultivation system*

A mixture of juvenile sporophytes and binding agent is taken from the hatcheries and transported to the sheet/nets by boat. The sporophytes are then sprayed onto the substrate (sheet nets) offshore at the field. No addition of nutrients will take place. Although higher yields are seen where nutrients are added, this is considered neither to be environmentally sound, nor to be feasible for large-scale operations. Instead, waters with high nutrient content (river runoffs, sewage outlets, sites adjacent to fish farms, etc.) may be preferred for the location of seaweed cultivation farms.

Maintenance of the deployed segments and field occurs throughout the year. When the seaweed is deployed/growing, maintenance includes checking, refastening, repairing and removal of waste etc. Because offshore operation maintenance is expensive (Burg, Duijn, Bartelings, Krimpen, & Poelman, 2016), maintenance is limited to checking, repairing and refastening between the deployment and harvest campaigns, e.g. after storms.

The Macrofuels cultivation system is designed to enable seaweed crop rotation for two harvests per year: in May (winter crop); and October (summer crop). The hourly capacity of the harvester has been set equal to the MacroFuels project objective of 1,000 m^2/hr effective area. Harvesting machines / platforms are transported by barge to the seaweed cultivation field for each harvest.

2.1.3 Conditioning and storage

Since biofuel production at large scale usually is a continuous process, it needs a year-round supply of high quality feedstock. Therefore, there is a need to preserve harvested seaweed biomass in order to minimise the degradation of the seaweed and the loss of organic matter.

The process for preserving seaweed is assessed as part of the MacroFuels project. The aim is to achieve a loss of sugars of no more than 5% over the storage period. Ensiling is the most appropriate option for the MacroFuels project, as it is most suitable for large-scale production.

2.1.4 Pre-treatment

Various pre-treatment technologies have been developed to hydrolyse the carbohydrates in seaweed to yield monomeric sugars suitable for fermentation or thermochemical conversion into biofuels. Some of these pre-treatment methods are evaluated as part of the MacroFuels project. Acid and enzymatic hydrolysis presents had been selected to be the most suitable method for MacroFuels. Hydrolysis is undertaken in a hydrolysis reactor, following which the solid residues and liquid phase are separated. The liquid phase is used to produce the liquid biofuels. The solid residues, containing non-hydrolysed organic matter, are sent to anaerobic digestion to produce biogas.

2.1.5 Conversion

In the MacroFuels project, the sugars obtained via pre-treatment are converted into biofuels or fuel precursors through fermentation and thermochemical conversion. Fermentation is used to convert the sugars obtained via pre-treatment into ethanol or to butanol, which is the main constituent of the ABE fermentation that produces a mixture of acetone, butanol and ethanol. A biphasic reaction concept is used to produce furanics. The organic residue from fermentation and thermochemical conversions is processed via anaerobic digestion to produce biogas, which is partly used for covering the internal heat demand. In large-scale production, it is envisaged that the remainder will form an integral part of the production of the biofuels, thereby improving the energy balance of the biofuel value chain.

2.1.6 Purification, storage, distribution and use

Separation of the biofuels from the dilute solution is required. For ethanol, this is achieved using distillation and dehydration. For butanol and furanic fuels, a combination and phase separation are used. Storage and distribution covers the transport from the refinery to the forecourt. Finally, use of biofuels implies the combustion of the fuel in an internal combustion engine. It covers the conversion of the fuel into energy with associated emissions.

3 INTEGRATED SUSTAINABILITY ASSESSMENT METHOD

This chapter sets out the overall method of the integrated sustainability assessment, which will build on the results of the assessments of the individual sustainability aspects of the seaweed biofuel systems – based on virtual and real-world systems. The individual assessments will be combined to evaluate the MacroFuels concept in relation to economics, environmental and social aspects, health and safety, and environmental risks. The findings will be integrated into an overall assessment, providing an overall picture of the different options and facilitating decision-making between the options.

There are a multitude of options for generating biofuels from seaweed according to the MacroFuels concept, as the description in Chapter 2 indicates. Rather than seeking to evaluate all of the possible value chains, the sustainability assessment will focus on selected scenarios, depicting the most likely routes for large-scale implementation based on current knowledge.

3.1 Overarching approach to evaluate sustainability

In the context of the MacroFuels project, a structured discussion approach to sustainability performance is preferred to a more quantitative resolution of trade-offs, involving the application of weighting factors to the indicators and combining these into a single 'sustainability' score. The latter might appear to be more 'scientific', but in practice depends on subjective value-based choices that may not immediately seem apparent. In addition, transparency may easily be lost in such an approach. At its current stage of development, any research findings will be crucial in informing decisions around future investment and policy initiatives for seaweed-derived fuels and, as such, transparency is paramount.

Thus, the overarching approach adopted for the integrated sustainability assessment is shown in Figure 3.1, based on a structured approach. The different stages include:

1. Collate indicators and results from the assessments of individual sustainability aspects;
2. Benchmarking of the findings based on a rating system; followed by a
3. Overall comparison and structured discussion (integrated sustainability chart)

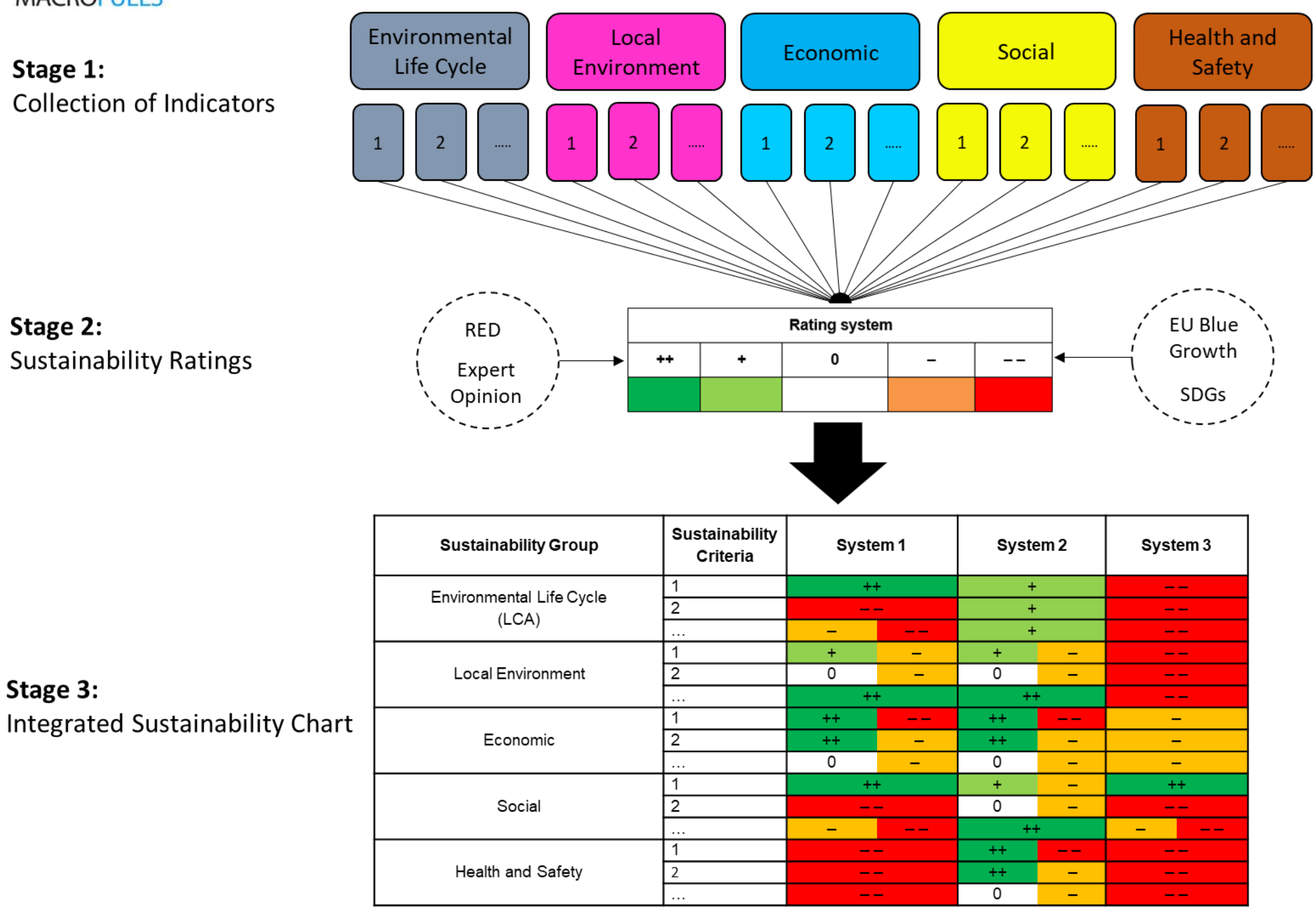

Figure 3.1 *Overarching approach to evaluate the sustainability performance of the MacroFuels concept*

3.2 Collation of indicators and results

The indicators and results used in the integrated assessment will be provided by the assessments of the individual aspects of sustainability. Those identified as relevant for supporting the assessment will be collated in overview tables and discussed. In some cases, the indicators may be aggregated or de-selected in order to focus on decision support. This might be necessary where related (qualitative) indicators show similar patterns for the scenarios assessed and, as such, can be merged into a more general indicator. Examples of indicators that may be excluded are those that show the same results for all of the scenarios assessed, or indicators that are rated as less important for informing decision-making by the respective experts.

3.3 Benchmarking based on sustainability ratings

The assessments conducted under the individual Work Package Tasks will, as part of the benchmarking process, generate quantitative and qualitative indicators expressing the differences between each scenario and the benchmark. As such, the comparisons serve to provide decision support with respect to whether, and to what degree, a scenario performs better than the benchmark.

In the integrated sustainability assessment, the tabular representation of quantitative and qualitative differences will be categorised based on a rating system (++, +, 0, –, – –) and colour coded to aid the comparison, shown in Table 3-1.

Table 3-1: *Example rating system.*

Rating system				
++	+	0	–	– –

The rating system for each sustainability aspect is defined by each work package lead. Further descriptions of rating systems are shown in following subsections.

3.3.1 Environmental LCA ratings

The rating system for the environmental LCA impact categories are based on a quantitative difference e.g. 25% better than the benchmark, shown in Table 3.2. In this case, the benchmark is ethanol from sugar beet[1] grown in the EU and the RED target for GHG emissions (climate change impact category).

Table 3-2: *Environmental LCA sustainability rating system based on biofuel (sugar beet) benchmark.*

Rating	++	+	0	–	– –
Definition	>75%*	75% - 100%*	No change (100%)	100% - 125%*	>125%*
Colour rating					

3.3.2 Local environmental impact ratings

The rating system for the local environmental impact categories are based on a subjective assessment of how the impacts relate to the EU blue Growth (EU, 2012) and the Sustainable Development Goals (SDGs) (UN SDGs, 2015), shown in Table 3-3.

[1] Ethanol, without water, in 95% solution state, from fermentation {CH}| ethanol production from sugar beet | APOS, U, based on ecoinvent v3.0.

Table 3-3: *Local environment sustainability rating system based on UN SDG and EU Blue Growth strategy.*

Rating	**++**	**+**	**0**	**–**	**– –**
Definition	Positive impact in line with UN SDG or EU strategies/policies - documented from cultivated seaweed in several environments	Positive impact in line with UN SDG or EU strategies/policies - documented from natural populations or cultivated seaweeds in few environments	**No change** (Documentation of no impact or no/negligible impact given mitigation)	Negative impact, counteracting UN SDG or EU strategies/policies - documented from natural populations and/or cultivated seaweeds in few environments	Negative impact, counteracting UN SDG or EU strategies/policies - documented from cultivated seaweed in several environments
Colour rating					

3.3.3 Social impact ratings

The rating system for the social impact categories is based on a combination of identified relevant impacts and risks in literature on aquaculture, expert judgement and the social hotspots database. A risk scoring system and stakeholder input that has been collected in focus group meetings with a Citizen Panel, set up by MacroFuels, with representatives from coastal communities in/near the project test seaweed farm locations.

Table 3-4: *Social sustainability rating system based on expert judgement, social hotspot database, and stakeholder input.*

Rating	**++**	**+**	**0**	**–**	**– –**
Definition	**Highly positive social impacts**	**Positive social impacts**	**Neutral or no change**	**Negative social impacts**	**Highly negative social impacts**
Colour rating					

3.3.4 Economic impact ratings

The rating system for the economic impact categories are based on expert judgement and comparison with a biorefinery and chemical operation. As a reference, the techno-economics of a 2nd generation corn stover to bioethanol plant were taken (Humbird, Davis, et al. 2011). For the fuels supply, a different rating was used where the potential fuel supply in Europe was assessed, given the potential very large cultivation area.

Table 3-5: *Economic sustainability rating system based on expert judgement and comparison with a biorefinery and chemical operations.*

Rating	**++**	**+**	**0**	**–**	**– –**
Definition	**Very positive –** significantly better than reference process	**Positive –** better than reference process	**Neutral –** in range of reference	**Negative –** worse than reference process	**Very negative –** significantly worse than reference process
Colour rating					

3.3.5 Health and safety impact ratings

The rating system for the health and safety impact categories is only for the biorefinery part of the chain. Health and safety considerations are certainly also of importance for the cultivation part of the chain. However,, these deserve a separate assessment that was defined within the scope of MacroFuels based on expert judgement and comparison with a conventional biorefinery or petro-chemical operations. The very positive aspects require inherently more safe operation for the full plant, while for very negative mitigation measures would require different safety regime. Also the introduction of unknown elements (operations, chemicals) that require further investigation will put processes in the rating class.

Table 3-6: *Health and safety sustainability rating system based on expert judgement and comparison with a biorefinery and chemical operation.*

Rating	++	+	0	–	– –
Definition	**Very positive –** inherently safer and/or heathier process compared to reference process	**Positive –** positive health and safety aspects compared to reference process	**Neutral –** comparable safety aspects compared to reference process	**Negative –** Additional health and safety aspects that can be managed with limited impact	**Very negative –** Additional health and safety go beyond normal impact mitigation measures; unknown elements that require further investigation
Colour rating					

3.4 Overall comparison and structured discussion

For an overall comparison, the structured overview tables containing the integrated assessment results will be supported by a discussion of the findings and the choice between options. This will connect the results of the individual assessments to give an integrated view on the sustainability of the MacroFuels biofuel concept.

The structured discussion with the MacroFuels value chain (environmental LCA, economic, social, health and safety aspects), followed by key insights learnt from the local environment of real-world small to medium-scale cultivation systems – located in Denmark and Scotland.

Lastly, the options to improve the sustainability performance across the different sustainability criteria and groups are provided to ensure the sustainable development of the MacroFuels technology towards large-scale commercialisation.

4 SUSTAINABILITY ASSESSMENT RESULTS AND DISCUSSION

4.1 Overall comparison and structured discussion

The sustainability results across the environmental LCA, local environment, social, economic, and health and safety are shown in Table 4.1. Overall, the sustainability assessment of the MacroFuel concept shows a mixed sustainability profile ranging from double negative to double positive. In some cases, a double score is presented where there is uncertainty. Further structured discussion is provided below, firstly on the MacroFuels value chain, followed by key insights learnt from the local environment of real-world small-scale cultivation systems – located in Denmark and Scotland.

Table 4-1: *Overall comparison of the sustainability results for the MacroFuels concept.*

Sustainability Group	Sustainability Criteria	Seaweed Cultivation Systems			Biofuel Conversion processes							
		Small-scale seaweed cultivation system (Denmark)	Small-scale seaweed cultivation system (Scotland)	Large-scale seaweed cultivation system (MacroFuels concept)	Ethanol enzyme hydrolysis (EtOH)	Ethanol acid hydrolysis (EtOH)	Ethanol enzyme hydrolysis (ABE)	Ethanol acid hydrolysis (ABE)	Butanol enzyme hydrolysis (ABE)	Butanol acid hydrolysis (ABE)	Furanic fuel	Furanics / butanol blend
Environmental (LCA)	Climate change	Not assessed	Not assessed	– –	–	– –	–	– –	–	– –	–	–
	Ozone depletion	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Human toxicity, cancer effects	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Human toxicity, non-cancer effects	Not assessed	Not assessed	++	– –	– –	– –	– –	– –	– –	– –	– –
	Particulate matter	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Photochemical ozone formation	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Acidification	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Terrestrial eutrophication	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Freshwater eutrophication	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Marine eutrophication	Not assessed	Not assessed	++	– –	+	– –	+	– –	+	+	– –
	Freshwater ecotoxicity	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Water resource depletion	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Mineral, fossil & renewable resource depletion	Not assessed	Not assessed	– –	–	– –	– –	– –	– –	– –	– –	– –
Environmental (local)	Hydrodynamics	+ / –	+ / –	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	Light	0 / –	0 / –	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	CO_2 uptake	++	++	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	Nutrient uptake	++ / –	++ / –	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	Biomass production	+ / –	+ / –	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	Oxygen production	+	+	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	Biodiversity	++ / – –	++ / – –	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
	Material loss	– / – –	– / – –	Not assessed	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Social	Economic growth and development	+ / 0	+ / 0	++ / – –	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Work place creation	+ / 0	+ / 0	+ / –	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Health & safety of work places	0 / –	0 / –	0 / –	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Effects on social burden from climate change	+	+	++	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Change to ecological status of living environment	+ / –	+ / –	++ / – –	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Effects on coastal erosion	0	0	++	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Revival of rural areas, incl. local infrastructure	0	0	++	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Influx of non-local workforce	++ / 0	+ / 0	++ / – –	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Public perception of blue economy	++ / – –	++ / – –	++ / – –	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
	Regional political empowerment	0	0	++	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
Economic	Biofuel supply	Not assessed	Not assessed	++	++	++	++	++	++	++	++	++
	Seaweed costs	Not assessed	Not assessed	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Sales revenue	Not assessed	Not assessed	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –
	Operating margin	Not assessed	Not assessed	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –	– / – –
	Capital investment	Not assessed	Not assessed	– –	– –				– –			
Health and Safety	Health	Not assessed	Not assessed	Not assessed	0 / –	0 / –	0 / –	0 / –	0 / –	0 / –	0 / –	0 / –
	Safety	Not assessed	Not assessed	Not assessed	0 / –	0 / –	0 / –	0 / –	0 / –	0 / –	0 / –	0 / –

4.1.1 Discussion on MacroFuels value chain – environmental LCA, economic and health and safety aspects

Based on the MacroFuels value chain, the environmental LCA assessed the whole value chain and clearly shows the majority of environmental impact categories are double negative (i.e. greater than 125% of the sugar beet benchmark). The major contributor is the growing equipment, accounting for up to 79% of the total impact, as shown for the GHG emissions in Figure 4.1.

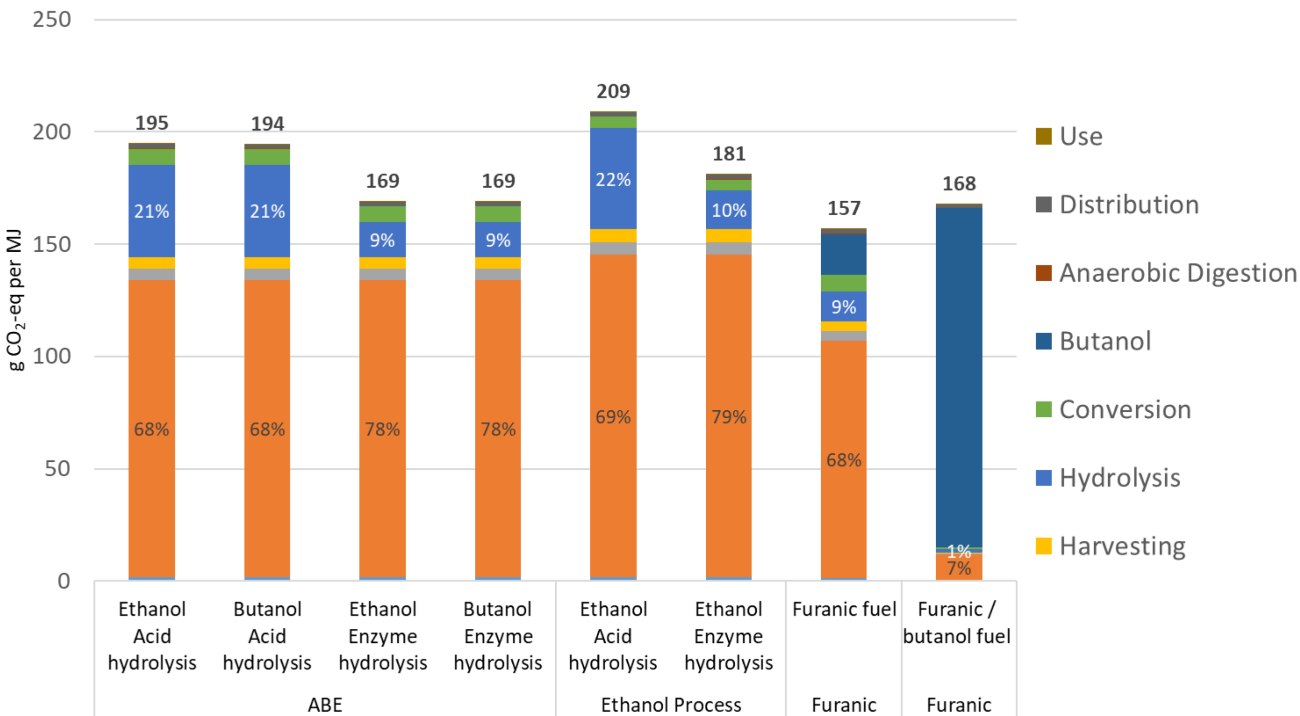

***Figure 4.1** Contribution of life stages to GHG emissions.*

Whilst 13 different environmental impact categories were assessed, the climate change impact category is by far the most important driver in developing the MacroFuel technology sustainably towards commercialisation, primarily due to the Renewable Energy Directive (RED). As reported in the environmental LCA shown in D6.4, benchmarking against the RED sustainability criteria and other fossil fuel (petrol and diesel) and current biofuel benchmarks (ethanol from sugar beet, ethanol form maize and ethanol from wheat straw) showed the following results.

- None of the baseline MacroFuel biofuels meet the RED sustainability criteria (32.9 g CO_2eq/MJ).
- The climate change impact of all of the baseline MacroFuel biofuels is greater than the fossil fuel comparator specified in the RED for transport fuels (> 94 g CO_2eq/MJ).
- The ‘cradle to grave’ climate change impact of all of the baseline MacroFuel biofuels is greater than petrol or diesel.

- The MacroFuel biofuels all have a significantly greater ‘cradle to grave’ climate change impact than the bio-ethanol produced from all the comparison bio-feedstock.

The analysis identified that the baseline MacroFuel biofuels have a greater climate change impact than the bio-ethanol produced from terrestrial-based bio-feedstock (sugar beet, wheat and maize) because:

- Seaweed produced under the MacroFuels concept has a greater climate change impact per kg (dw) of feedstock than sugar beet or, wheat or maize; and

- The energy yield of all of the co-products produced under the MacroFuels concept (including all biogas produced) is lower than the energy content of ethanol produced from the conventional terrestrial bio-feedstock on a dry weight basis.

The main contributors to all of the environmental impact categories assessed were either the seaweed cultivation equipment or the hydrolysis process step. Other notable contributions from other sources were made for the following impacts.

- **Ozone depletion:** for ethanol and butanol produced via enzyme hydrolysis, the contributions from cultivation, harvesting and conversion to biofuel are significant, each accounting for approximately 13% of the total impact.
- **Freshwater eutrophication:** for ethanol and butanol produced via enzyme hydrolysis, the life cycle stage for conversion to biofuel is also significant, accounting for 25% of the total impact.
- **Marine eutrophication**: for all of the MacroFuel biofuel scenarios, the cultivation and harvesting steps each account for approximately 10% of the total impact.
- **Terrestrial eutrophication:** for all of the MacroFuel biofuels, the life cycle stages for cultivation and harvesting are also significant, each accounting for approximately 11% and approximately 14% of the total impact, respectively.
- **Photochemical ozone formation:** for all of the MacroFuel biofuels, the life cycle stages of cultivation and harvesting are also significant, each accounting for approximately 11% and approximately14% of the total impact, respectively.

Considering economic aspects, the sustainability results generally show a negative sustainability profile. In particular, the seaweed costs were found to be significantly higher compared to other fossil-based fuels e.g. €18 per kg dry weight for seaweed compared to current prices of < €1 per kg fossil fuels). The revenues are lower than the reference case, and the operating margin (difference between operational costs and revenues) is negative as a result of the high seaweed costs. The investment required is high for both the cultivation and for the biorefinery. Typically, the investments are higher than for the reference biorefinery. The investments for the cultivation unit are also significant. Whilst the cost difference is significant, it should be noted that the MacroFuels concept is at an early stage of development. For technologies at this stage typically large, step-wise, improvements can often be made. In addition, compared to fossil-fuels there is a renewable source of bio-fuels where the economic potential is higher.

For health and safety (H&S) aspects, an assessment of the relevant substances shows an impact for some of those that are used or produced. Amongst these are flammable liquids (acetone, butanol, ethanol, toluene, furanics etc.) and biogas. Substances with health risk are the acid and base used, intermediates and products from furanics production. However, all of these are commonly applied in biorefineries and in the petrochemical industry and these risks can be mitigated with conventional measures to comply with regulations.

The large-scale cultivation of seaweed is a novel operation for Europe, for which the main concerns are related to the safety risk for personnel during the mechanical operations seeding, deployment and harvesting. The level of automation is an important determinant of risk. A second novel operation is the large-scale ensiling and storage of seaweed. Incidents could occur in which butyric acid or H_2S could be formed and the venting system needs to be equipped appropriately for the removal of these substances. Finally, in the furanics route, novel components are produced, for which a safety and health assessment is likely to be required.

Overall, whilst the environmental LCA and economic aspects are based on the MacroFuels concept, the local environment aspects are based on real-world small to medium-scale cultivation systems that can reveal sustainability insights relevant for a large-scale seaweed cultivation system. Some of these key insights are described as follows:

4.1.2 Discussion on local environment aspects

A mixed, but overall positive, sustainability profile across the following impacts categories: CO_2 uptake; oxygen production; pH increase; nutrient uptake; biodiversity; light; loss of synthetic and organic materials; and hydrodynamics.

- **CO_2 uptake** – climate change mitigation: like plants on land, seaweeds live through photosynthesis, using sunlight to convert CO_2 into sugars. The CO_2 uptake of seaweeds is equivalent to approximately 1.3 tonne of CO_2 per tonne of seaweed dry matter. The carbon from seaweed biomass can substitute for fossil carbon i.e. in fuels. Only a minor fraction of the CO_2 taken up by seaweeds is sequestered. Two other beneficial consequences of seaweed photosynthesis is the production of oxygen, which is needed by marine animals, and an increase of sea water pH, which counteracts ocean acidification. However, seaweeds also emit climate active gases such as halocarbons, dimethylsuphide (DMS) and nitrous oxide. More research is needed to document the scale and consequences of these releases.
- **Nutrient uptake** – counteracting eutrophication: seaweeds need nutrients to grow, and efficiently take up nitrogen and phosphorus from the surrounding sea water. When harvesting the seaweeds, nutrients are removed from the marine system and made available for the bio-economical system on land (5-60 kg N per tonne of seaweed dry matter). In most European coastal waters, nutrient emissions from human activities on land and aquaculture lead to eutrophication and reduced marine environmental quality. The EU Water Framework Directive demands accelerating the recovery of marine ecosystems from eutrophication. In eutrophic areas, seaweed cultivation could counterbalance the anthropogenic inputs of nutrients.

However, in nutrient-poor marine areas, competition for nutrients may limit seaweed productivity, whilst having a negative impact on natural marine ecosystems. Site selection based on coupled hydrological-ecological modeling is needed.

- **Biodiversity** – Introducing a seaweed cultivation system into the marine environment, will increase the habitat complexity. The cultivation structure itself, as well as the seaweeds when growing, will provide feed, shelter and substrate for mobile and sessile marine organisms, increasing local biodiversity. However, 'un-wanted' species – non-native species, diseases and parasites, may also use the cultivation system as a vector for further dispersal. Intensive cultivation of a seaweed mono-crop may in itself contribute to the spread of seaweed diseases and pests to natural seaweed populations. Regarding genetic diversity, caution should be taken not to introduce and cultivate non-local cultivars, as the spread of genes to local populations cannot at present be avoided, and may lead to genetic depression. It is strongly recommended that only native species and local genetic cultivars are cultivated.
- **Reduction of light to the seafloor** – A "hanging seaweed forest" in the surface waters will absorb a fraction of the incoming light, and hence reduce the input of light to the sea floor for natural populations of seagrass, seaweeds and benthic microalgae. The impact will depend on the scale and density of the cultivation. Placing of cultivation areas beyond the depth limits of natural benthic vegetation will minimize the negative impact.
- **Loss of synthetic materials** – Cultivation materials are typically produced from durable synthetic materials such as plastics, nylon and polypropylene. Loss of material is difficult fully to prevent, and may cause damage to maritime activities or to marine animals, due to entangling or consumption. Standards and regulations for site management, as for other aquaculture activities, will minimize this risk.
- **Loss of organic material** – During growth, seaweeds will naturally loose dissolved and particulate organic material to the environment. Some of this will stimulate the production of the local food web in the water column and in the sediment beneath the seaweed, and some may be buried in the seabed. If larger amounts of organic material are accumulated below the seaweed, local oxygen deficiency and impoverishment of the benthic biodiversity may occur. Site selection and site management will contribute to minimizing these risks of negative impacts.
- **Local current and wave patterns** – Seaweed cultivation structures will influence the local hydrology (current patterns and wave action). This may affect the water exchange inside the cultivation area, and with this the access of the seaweeds to nutrients, the local patterns of sediment transport, the coastline, as well as the structure and productivity of local marine food webs. Site selection based on hydrological modelling will contribute to minimizing these risks of negative impacts.

4.1.3 Discussion on social aspects

Overall, the social impacts of an assumed mature MacroFuels seaweed-to-biofuel value chain are positive, with the potential for highly positive effects for some impact categories.. The assessment is based on a value chain built on sound practice and cultivation site selection. Nevertheless, even with best practice, a few social risks remain. There are good mitigation options available for some of these, whilst others will have to be socially accepted and/or consensus will have to be built.

Positive to highly positive impacts can be expected for the following social impact categories.

- Highly positive impacts can be expected in terms of economic growth, based on a growing seaweed-based industry. This has a particularly high relevance for coastal communities. The overall socio-economic impacts are expected to be more relevant in remote and rural areas, rather than in already more industrialised regions. Establishing seaweed as biomass for advanced fuel could further boost the European seaweed cultivation industry, based on the expectedly large market segment that can be targeted. The higher availability of biomass could support a change towards a market pull for seaweed-based products. However, policies and the public will for seaweed-based fuels are needed to overcome the initial market barrier of fuel price.
- A highly positive impact can be expected from the creation of work places in different work areas, requiring varying levels of qualification and training. With growing demand for seaweed as biomass for various applications within the European Bioeconomy, it is likely that further economic players that deploy seaweed as biomass (e.g. the food, feed, biomaterials, fertiliser and pharmaceutical industry) will locate themselves near seaweed production sites. This will result in an even larger number of work places in the processing industry, e.g. in biorefineries and manufacturing industry, including high quality and high salary work places in biotechnology, chemistry, engineering etc.
- In the long term, economic growth and a multitude of opportunities for the bioeconomy could result in an improved economic status of coastal regions, especially through increasing fiscal revenues. However, this depends on local or regional development strategies (e.g. the inclusion of the blue economy in smart specialisation strategies) and policy support.
- An overall positive impact at a societal level can be expected from the decarbonisation of transport by advanced and sustainable biofuels. However, this effect depends on the actual sustainability performance of the biofuel in question.
- The effects of seaweeds' CO_2 and nutrient uptake, their ability to release oxygen in the ocean and their effect on biodiversity in large-scale cultivation systems could help to lower the societal burden resulting from climate change and result in the improved health of the ocean and coastal living environment and especially benefit coastal communities. Other users of the ocean space, e.g. fishermen, other aquaculture, tourism etc.) would also benefit.
- Based on the effects on local wave energy and current patterns, seaweed cultivation structures located in areas that have been proven to be vulnerable to coastal erosion, may help to dampen the wave energy and that way could help to prevent or decrease the extent of erosion by high wave energy. This could improve the living environment for coastal communities threatened by high erosion rates by the ocean.
- Traditionally, infrastructure develops in an economically thriving region, and positive socio-cultural impacts will result from an overall revival of rural areas and of regions that lack other

economic specialisation opportunities.. This is promoted by the growing need for infrastructure, such as public transport, medical care, schools, kindergartens etc. to serve a growing workforce (incl. commuters) and the influx of non-local workers.

- With regard to the access to resources, expected impacts are highly positive, as for economic reasons the cultivated biomass is not likely to be used exclusively for fuel production, but will represent a novel biomass for local and regional entrepreneurial activity. In particular, existing local entrepreneurs currently self-employed in aquaculture (mussel farmers, seaweed entrepreneurs using seaweed from wild harvest) could unlock new sources of income or opportunities for business growth and expansion.
- Further highly positive effects are assessed for a good financial status and diversified economic opportunities that are expected to lead to regional empowerment at political levels. Sound regional development strategies could further increase the political influence of regions with a strong seaweed economy.

A number of socially ambiguous effects and social risks emerge from large-scale seaweed cultivation, even if seaweed farms use best practices and carefully selected cultivation sites, as follows.

- A social risk emerges from the growing industrialisation of rural areas based on large-scale seaweed production and the processing industries. This could result in low public acceptance towards the upscaling of seaweed production and processing, especially in rural, coastal and often remote areas.
- A negative effect in the labour market relates to the potential creation of a low wage sector with seasonal work and added health and safety risks in seaweed production and harvesting. Although these negative effects could be avoided by automated processes in seeding and harvesting, this could result in the displacement of labour, which weakens the impact of work place creation.
- Competition over ocean space, e.g. with fisheries, leisure and tourism, wind parks, and other aquaculture, represents a negative social impact which can be mitigated by the promotion of co-use scenarios in the use of ocean space and smart maritime spatial planning.
- Poor site selection, or insufficient farming standards, pose a social risk as these could lead to a negative environmental performance of seaweed farming, unwanted negative effects on hydrodynamics and an overall a less desirable living environment of coastal communities. This could further result in a negative public perception of large-scale seaweed farming. Good site selection tools and farming standards can avoid such risks.

4.2 Options to improve sustainability

In this section, options to improve sustainability performance of the MacroFuels concept are presented fo environmental LCA, social, local environment, economic, and health and safety. The impact of options to improve sustainability are subjective and require future work to investigate optimal benefits.

4.2.1 Environmental LCA

The sustainability ratings for the environmental LCA aspects (D6.4) for the baseline Macrofuels concept and after implementing options to improve are shown in Table 4.2.

Table 4-2: *Summary of options to improve sustainability performance of environmental LCA aspects.*

Impact category	Rating	Improvement options	Rating after improvement
Climate change	++ – –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material	++ –
Ozone depletion	– –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Decrease enzyme use	–
Human toxicity, non-cancer effects	++ – –	1. Decrease enzyme use 2. Use acid hydrolysis 3. Use less materials	++ –
Human toxicity, cancer effects	– –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material 5. Decrease enzyme use	–
Particulate matter	– –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material 5. Include digestate benefit	–
Photochemical ozone depletion	– –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material 5. Decrease seeding/harvesting fuel use	–
Acidification	– –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material 5. Decrease enzyme use	–
Terrestrial eutrophication	– –	1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material 5. Decrease seeding/harvesting fuel use 6. Include digestate benefit	–

Freshwater eutrophication	– –		1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Include digestate benefit 5. Decrease enzyme use	–	
Marine eutrophication	++	–	1. Decrease enzyme use 2. Use less materials	++	0
Freshwater ecotoxicity	– –		1. Use acid hydrolysis 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Include digestate benefit 5. Decrease enzyme use	–	
Water resource depletion	– –		1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material	–	
Mineral, fossil & renewable resource depletion	– –		1. Increase seaweed yield 2. Use less materials 3. Increase lifetime of grow-out equipment. 4. Use recycled material 5. Include digestate benefit	–	

Across the majority of environmental impact categories, the options to improve the sustainability ratings are as follows.

1) **Increase seaweed yield** – to explore other regions of Europe (e.g. Spain and Portugal) with higher possible yields.
2) **Use less materials –** by decreasing the materials used in the grow-out unit.
3) **Increase lifetime of grow-out equipment** – to extend current growing equipment beyond 10 years.
4) **Use recycled materials** – to increased recycled content towards 100% and promote a circular blue economy.
5) **Decrease enzyme use** – to reduce enzyme use during hydrolysis.
6) **Include digestate benefits** – to attribute environmental savings for the digestate.

The climate change impact category improvement option are particularly affected by increase in seaweed yield, increase in grow-out equipment lifetime and use of recycled materials. The use of recycled material shows the greatest improvement for the impact category. The inclusion of the digestate benefit offers an improvement in the climate change category, but it is not as significant as those previously mentioned. By comparison, the climate change impact category is significantly less sensitive to enzyme use and decrease in seeding/harvesting fuel use, with very little improvement seen.

For the other impact categories, an improvement is always seen for the increase in seaweed yield, increase in grow-out equipment lifetime and inclusion of digestate options. The degree to which the impact categories improve as a result of these options varies with the process type and impact category. The use of recycled content does not show an improvement across all impact categories. Ozone depletion, human toxicity, non-cancer effects, freshwater eutrophication and freshwater ecotoxicity are all negatively affected by the use of recycled material.

4.2.2 Local environment

The sustainability ratings for the local environment (D6.5), including before and after implementation options to mitigate risks are shown in Table 4.4.

Table 4-4: *Summary of options to improve the sustainability ratings of local environment aspects.*

Impact category	Rating		Improvement options	Rating after improvement	
Hydrodynamics	+	–	Site selection	+	0
Light	0	–	Site selection	0	
CO_2 uptake	++		n/a	++	
Nutrient uptake	++	–	Site selection	++	
Biomass production	+	–	1. Site selection 2. Site management	+	0
Oxygen production	+		n/a	+	
Biodiversity	++	– –	1. Use native species 2. Use local ecotypes / cultivars	++	–
Material loss (synthetic)	–	– –	Site management	0	–

In general, the sustainability profile for local environment aspects is mixed, butpositive overall. For all impact categories, the key strategies to mitigate impacts to the local environment are preferably through robust model-based site selection and responsible site management. For biodiversity, it is also recommended that the precautionary principle is adopted and the cultivation of non-native species and non-local ecotypes/cultivars is avoided or limited.

Impacts on the local marine environment of large-scale seaweed cultivation will depend on the local geology, hydrology and ecology conditions. Development of systematic site selection tools, based on hydrological and ecological modelling, will be crucial to optimise production and ecosystem services, in order to benefit from positive impacts and minimise negative impacts. The approach to site selection should be considered across all impact categories, with some specific considerations taken for certain categories. For example, the light impact category site selection should allow the farm to be beyond the depth limits of benthic vegetation. In addition, choosing a site that can optimise the harvest yield while not providing competition for nutrients in oligotrophic systems, will improve the nutrient uptake and biomass production impact categories.

Standards and regulations needs to be developed for a ‘Best Cultivation Practice’ for establishing and operating seaweed cultivation systems. Standards and regulations should include: site selection; baseline surveys; selection of structure and materials; site management; monitoring practice; and education. For the synthetic material loss category, best cultivation practice and securing the resilience and service life of the cultivation system components are the best strategies for site management.

The largest potential risk on the local marine environment is the spreading of non-native or harmful species such as seaweed diseases and pests to natural seaweed populations, or the introduction and spreading of genes from non-local cultivars that outperform local genes in the short run, but in the long run cause genetic depression and reduced fitness of local cultivars. A baseline knowledge of local species and genetic diversity needs to be established, which should include the prevalence of non-native species, seaweed diseases and pests. Development of biosecurity programs, including rapid diagnostic tools and quarantine procedures must be included in future standards and regulations. The use of native species and local ecotypes/cultivars will improve the biodiversity category by reducing the risk of spreading diseases, pests and genes to the natural kelp populations.

4.2.3 Economic

The sustainability ratings for the economic aspects (D6.2) including before and after implementation options for improvement are shown in Table 4-5.

Table 4-5: *Summary of options to improve the sustainability ratings of economic aspects.*

Impact category	Rating	Improvement options	Rating after improvement

Biofuel supply	++		n/a	++	
Seaweed costs	– –		1. Reduce number and weight of growing equipment materials, further mechanisation to reduce operational costs 2. Improve logistics of seeding and harvesting. 3. Reduce storage and biorefinery costs by concentrating streams and integrate operations. 4. Produce high-value co-products	–	
Sales revenue	–	– –		0	–
Operating margin	–	– –		0	–
Capital investment	– –			–	

In general, the majority of economic aspects are very negative, apart from the economic potential of biofuel supply. Due to the interrelated nature of costs across different criteria, the options to improve are applicable for seaweed costs, sales revenue, operating margin, and capital investment. These include:

1) Reduce the number and mass of growing equipment materials;
2) Improve the logistics of seeding and harvesting;
3) Reduce storage and biorefinery costs by concentrating streams and integrate operations; and
4) Produce high-value co-products.

Further automation of construction and assembly could reduce costs for the grow-out unit. Further automation of seeding and harvesting could lead to a reduction in operating costs.

The largest impact would be from the reduction of the cost of purchased equipment, specifically a reduction in the cost of buoys, sheet nets and chains. However, this should not compromise the cost of seeding and harvesting, as these costs are of equal importance. Storage and ensiling of seaweed make a large contribution to the overall costs and lowering these through alternative concepts or equipment would make a significant improvement. However, no suggestions as to alternatives have yet been made. For the acid hydrolysis routes, due to the large amount of water present in the seaweed and the addition of water in the hydrolysis step, large amounts of acid and base are used. However, the routes using enzymatic hydrolysis have much lower costs and are the preferred route over acid hydrolysis. Bringing down the addition of water would decrease the use of acid or enzymes and would also limit the large mass flow streams in the system and thereby reduce investments.

4.2.4 Social

The sustainability ratings for the social aspects (D6.3) including before and after implementation options for improvements are shown in Table 4.3.

Table 4-3: *Summary of options to improve the sustainability ratings of social aspects.*

Impact category	**Rating**		**Improvement options**	**Rating after improvement**	
Economic growth and development	++	– –	Consensus building in dialogues that include civil society representatives; stepwise upscaling to avoid public acceptance risks related to industrialisation	++	–
Work place creation	++	–	Social standards as part of seaweed farm licenses to avoid low wage sectors; consensus building about automated processes with civil society, focusing on health & safety	++	0
Health & safety of work places	0	–	Automated processes for seeding and harvesting at sea to avoid health and safety risks.	+	0
Effects on social burden caused by climate change	++		None	++	
Change to ecological status of living environment	++		None	++	
Effects on coastal wave regimes	++		None	++	
Revival of rural areas, incl. local infrastructure	++		None	++	
Influx of non-local workforce	++	– –	Sound integration strategies and measures for non-local residents, including living spaces, public meeting places etc. could avoid possible risks of lack of social cohesion due to influx.	++	–
Public perception of large-scale seaweed production and blue economy	++	– –	Assess, share and agree e.g. environmental impacts, discuss results and agree on acceptable levels of change	++	–
Regional political empowerment	++		None	++	

In general, the majority of social impact categories show very positive results. However, for impact categories that require improvement, the options to achieve this include the following.

1) **Economic growth and development –** to involve communities in planning, listening and adjusting concepts to assure consensus about industrialising rural and coastal areas and secure public acceptance and support.
2) **Work place creation –** to include social standards in seaweed farm licenses to avoid low wage sectors and to build consensus about the mechanisation / automation of processes, especially in seeding and harvesting.
3) **Health and safety of work places –** to increase automation during seeding and harvesting to reduce labour risk.
4) **Influx of non-local workforce –** to put an emphasis on sound integration efforts of non-local wok forces by local government and communities and/or develop training schemes for the local workforce to benefit from novel employment opportunities.
5) **Public perception of blue economy** – especially for coastal communities, a share in economic opportunities and involve civil society representatives in planning; assess, share and agree e.g. environmental impacts, discuss results and agree on acceptable levels of change

Dialogues with residents at MacroFuels test farm locations revealed that the main local concerns related to large-scale seaweed cultivation include the visual impacts of the farm, noise and dirt pollution by mechanised harvesting, competition over the marine space (esp. local fisheries, threat to native species, habitat extraction harming the marine fauna, loss of cultivation equipment polluting coastline and farming equipment causing entanglement of marine mammals. All of these risks can be mitigated either via sound farming practices or smart marine spatial planning and addressed by engaging closely with local/regional stakeholders, including civil society, to include local knowledge and give locals a share in the endeavour. Sharing knowledge with wide groups can avoid risks and maximise benefits, especially when policy makers at regional, national and EU levels are included.

4.2.5 Health and safety

The sustainability ratings for the health and safety aspects (D6.2) including before and after implementation of options for improvement are shown in Table 4.6.

Table 4-6: *Summary of options to improve the sustainability ratings of health and safety aspects.*

Impact category	Rating		Improvement options	Rating after improvement
Health	0	–	Increase automation of processes	0
Safety	0	–		0

Options to improve the sustainability rating of both health and safety are primarily associated with increasing automation. Although not assessed in detail for this project, it is expected that most health and safety risks are associated with the cultivation and harvesting stages. As these stages are fairly novel, health and safety risk mitigation options are not well known. On the other hand, the risks associated with the biofuel processing stages are similar to common biorefinery or chemical operation risks, and so current established industrial best practices can be used. Risks associated with the novel elements of seaweed storage are expected to be mitigated to conventional standards, and additional safety studies may mitigate this risk. Provisional health and safety classification of the furanics fuels suggest that these component have safety aspects comparable to reference fossil fuels. Nevertheless, a thorough characterisation and hazard classification (REACH) is to be performed before market introduction.

5 CONCLUSIONS

This report provides an integrated sustainability assessment of the MacroFuels project, covering a range of sustainability criteria for the environmental LCA, economic, social, local environment, and health and safety impact categories.

A bespoke sustainability assessment method was developed that integrated different sustainability criteria into an integrative colour chart. The stages of the method included the following: (1) collation of indicators and results from the assessments of individual sustainability aspects; (2) benchmarking of the findings based on a rating system; and (3) an overall comparison and structured discussion.

Overall, the sustainability assessment of the MacroFuels concept presented a mixed sustainability profile, with impacts ranging from very negative to very positive. The key conclusions are as follows.

- The results for the majority of environmental LCA impact categories are very negative (i.e. greater than 125% of the sugar beet benchmark (Inc. land use impacts)). The major contributors are the growing equipment, accounting up to 79% of the total.
- The GHG footprint is significantly higher than the RED target, fossil fuel and alternative biofuel benchmarks.
- Economic aspects are generally very negative, due to the early stage of technological development (e.g. low TRL (technology readiness level)). The economics could be significantly improved by producing multiple products that are of higher value, e.g. pharmaceutical, cosmetic and food ingredients.
- Impacts to the local environment range from highly positive to negative depending on the site. When suitable sites are selected, the impacts to the local environment are generally positive.
- Social impacts in general, and at both regional and local levels, are predominantly positive to very positive. However, a number of social risks remain. Most of these can be mitigated by social standards, sound practice and the involvement of civil society via co-development and dialogues.

6 RECOMMENDATIONS FOR FUTURE WORK

Whilst the mixed sustainability profile is ambiguous, it should be noted that the MacroFuels concept is at an early stage of development compared to alternative biofuels that have received many years of research, development and investment.

In order to improve sustainability performance, recommendations for future work focus primarily on improving the GHG footprint and economics to ensure the development of the MacroFuels technology sustainably towards commercialisation. These include the following.

1) **Expand the portfolio of high-value products derived from the macroalgae biomass** – by focusing on high value compounds, e.g. pharmaceutical, cosmetics and food and feed ingredients.
2) **Improve cultivation costs –** by improving operational (e.g. cost of seaweed is the main cost contributor) and capital costs and increasing equipment lifetime.
3) **Increase seaweed yield** – by exploring other regions of Europe (e.g. Spain and Portugal) with higher potential yields.
4) **Optimise cultivation practices** – by adopting all-year round cultivation.
5) **Use less materials –** by decreasing the materials used in the grow-out unit.
6) **Increase lifetime of grow-out equipment** – by extending the lifetime of current growing equipment beyond 10 years, based on improved corrosion-resistant materials.
7) **Use recycled materials** – by increasing recycled content towards 100% which can promote a circular blue economy.
8) **Decrease enzyme use** – by reducing enzyme use during hydrolysis.
9) **Include digestate benefits** – by attributing environmental savings associated with the digestate in GHG accounting.
10) **Alternative cultivation systems** – to explore systems where iron or galvanised steel (chains) are substituted by ropes, as found in France or the Faroe Islands, which could potentially lower environmental impacts and economic costs.

Overall, such measures should be taken as part of a holistic and optimised approach that aims to minimise materials use and natural resources and to secure social licenses for large-scale seaweed production and industrialisation of rural areas.

7 ACKNOWLEDGEMENT

This deliverable is part of the MacroFuels project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654010.

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9 ABBREVIATIONS AND GLOSSARY

9.1 Abbreviations

ABE	Acetone-butanol-ethanol
IBE	Isopropanol-butanol-ethanol
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
S-LCA	Social life cycle assessment

9.2 Glossary

Biofuel	Liquid or gaseous fuel for transport produced from biomass.
Biomass	The biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as biogases and the biodegradable fraction of industrial and municipal waste.
Furanics	Furanics refer to compounds with a furan ring in their structure.
Residue	Aqueous material which is the by-product of a processing step.
Reference product	Conventional or alternative product of identical utility, which is compared to an assessed product.
Sustainable biofuel	A biofuel fulfilling the sustainability criteria set out in Article 17 of Directive 2018/2001/EC.