

Environmental Assessment: Life Cycle Assessment of biofuels from seaweed using the MacroFuels concept

MacroFuels – Project

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Summary

Introduction

The objective of the MacroFuels project is to advance the technologies for producing liquid transportation biofuels from cultivated seaweed (or macroalgae). As a result, it is hoped that it will be possible to provide more sustainable transport fuels.

The MacroFuels concept sets out to progress the technologies for producing third generation biofuels from seaweed by assessing current system design concepts. These designs are informed by lab scale testing, field trials and modelling completed within the other work packages of the MacroFuels project. The biofuels production scenarios targeted as part of the MacroFuels concept are:

- Bio-ethanol via fermentation (EtOH process);
- Bio-butanol and bioethanol via ABE (acetone, butanol and ethanol) fermentation (ABE Process); and
- Bio-furanics via biphasic reaction with toluene and water, and reaction with bio-butanol and hydrogen.

This study reports an environmental life cycle assessment (LCA) of those biofuels which could be produced under the MacroFuels concept. The LCA evaluates the full value chain and thereby provides a better understanding of the potential environmental impacts of the large-scale cultivation of seaweed and its use as a feedstock for the production of biofuels.

A key driver for the development of biofuels in Europe is the renewable Energy Directive (2018/2001/EC) (the RED). The RED sets a target of 14% of energy for transport to come from renewable sources by 2030. For a biofuel to count towards this target, it must fulfil certain sustainability criteria set out in the RED with respect to greenhouse gas (GHG) emissions and should be identified as no / low risk for additional impacts from indirect land use change. Indirect land use change can increase the net GHG emissions from terrestrial crops used as biofuels, but seaweed is seen as a low risk crop in this context, as it is grown in the sea and will not displace land used to grow food.

Goal and Scope of the Study

The goal of this LCA was to conduct a 'cradle-to-grave' assessment of the MacroFuels concept. This will inform its future development by appraising the potential environmental impact of producing biofuels from seaweed for use as transport fuels and allow comparison of the calculated GHG emissions of these fuels with reported values for those produced from other sources.

The objectives of the LCA are as follows:

1. To increase MacroFuels' understanding of the life cycle environmental impacts of the biofuels from seaweed concept;
2. Identify where the main environmental impacts occur (the so-called 'hotspots') in the full value chain for the production of biofuels from seaweed to support the design of systems for seaweed cultivation and processing to biofuel;
3. Compare the life cycle impacts of the ethanol, butanol and furanic fuels produced; and
4. Benchmark the biofuels assessed under the MacroFuels project against:
 - a. Equivalent conventional, fossil-based, fuels and currently available biofuels; and
 - b. Sustainability criteria for GHG emissions under the Renewable Energy Directive (2018/2001).

Product System Studied and Functional Unit

The study investigates the potential environmental impacts of the following products produced via the three processes outlined above. An important step in both the EtOH and ABE processes is the hydrolysis of the seaweed prior to fermentation. This can be completed by either acid hydrolysis or enzyme hydrolysis and both processes are considered, as follows.

- Ethanol (EtOH process - acid hydrolysis);
- Ethanol (EtOH process - enzyme hydrolysis);
- Ethanol (ABE process - acid hydrolysis);
- Ethanol (ABE process - enzyme hydrolysis);
- Butanol (ABE process - acid hydrolysis);
- Butanol (ABE process - enzyme hydrolysis);
- Furanics fuel additive; and
- Furanics fuel (10%) / bio-butanol (90%) blend

The functional unit this study is defined as:

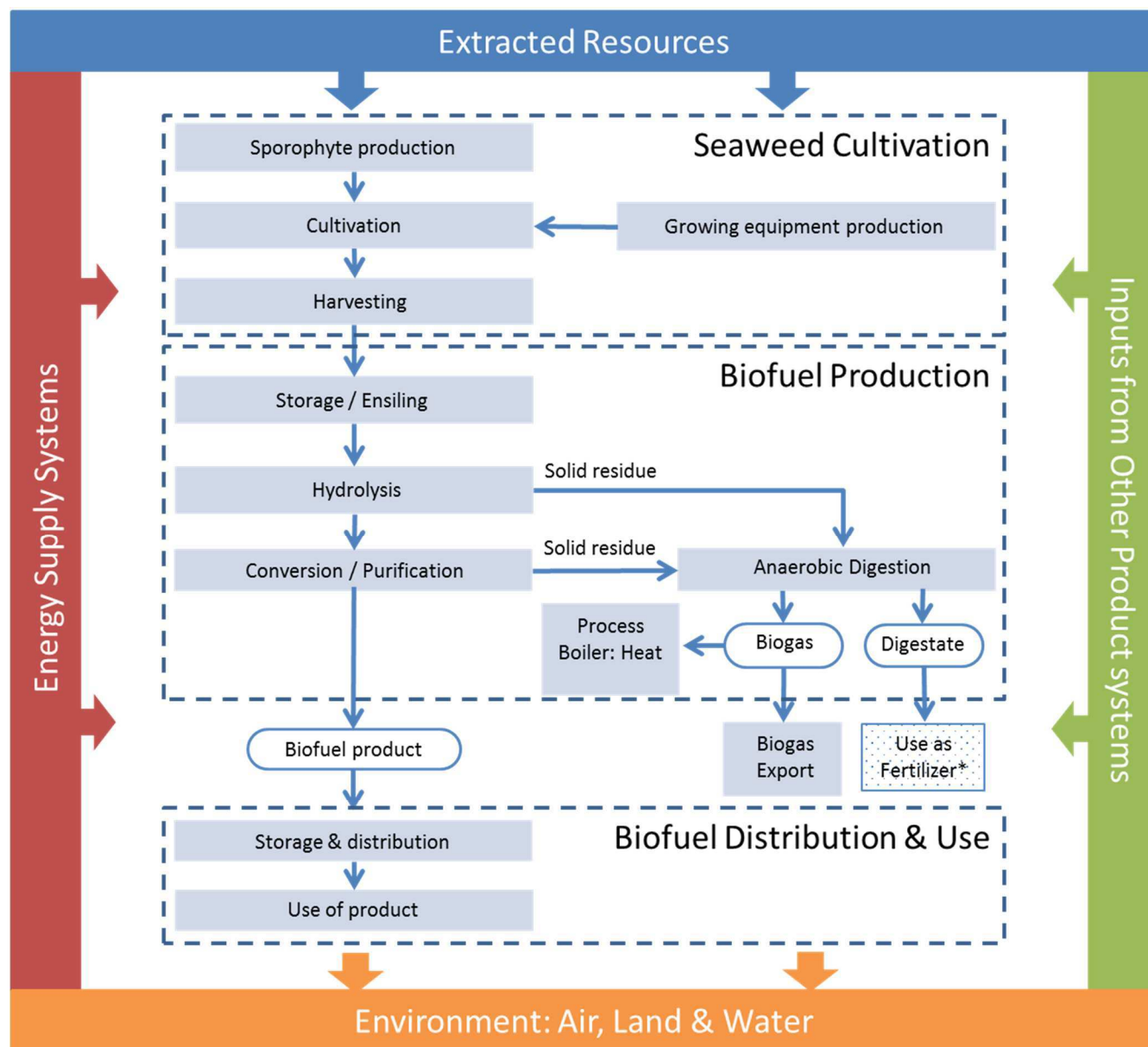
1 MJ of biofuel used as transport fuel in an internal combustion engine.

Life Cycle Stages Considered

The LCA carried out was 'cradle-to-grave'. This means that all significant life cycle stages associated with the product systems studied were considered, from raw materials, through processing and production, to distribution, use, waste collection, recycling or management at end of life.

Energy and material inputs were traced back to the extraction of resources, and emissions and wastes from each life cycle stage were quantified. Figure 0-1 shows the system boundary of the LCA.

Figure 0-1 System boundaries of LCA based on life cycle of biofuel from seaweed according to the MacroFuels concept



The Macrofuels concept considers a biorefinery with a processing capacity of 1.2 Mtonne seaweed (dw) per year, as this equivalent to that of an existing large bioethanol plant in the port of Rotterdam, the Netherlands.

Seaweed cultivation

The 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. It has been assumed that two harvests a year of these crops is possible. The cultivation systems and yields for both seaweeds are assumed to be the same.

The design of the seaweed cultivation system was based on a concept published in open literature (Groenendaal, Vandendaele, & Vroman, 2017; Sioen, 2015). The growing substrate for the seaweed is sheetnets, made from polyester non-woven material, held horizontally in the water by chains and bouys and arranged in repeating segments for a total effective area of the seaweed field of 18,460 ha. This will produce 1.2 Mtonne seaweed (dw) per year for the biorefinery.

Processing seaweed to biofuel

The data for processing seaweed to biofuel have been sourced from MacroFuels deliverable 6.2, *Techno-economic Evaluation and Health and Safety Risk Assessment*. Table 0-1 below summarises the production processes for each scenario considered in the Macrofuels concept.

Table 0-1 an overview of the biofuel production process for each biofuel scenario

Process Stage	EtOH process	ABE process	Furanic fuel
Storage / Ensiling	Seaweed ensiled using lactic acid bacteria to prevent seaweed degradation		
Hydrolysis (Acid or Enzymatic)	<p>Acid hydrolysis using hydrochloric acid to break down the sugars in the seaweed. The residual acid is neutralized with sodium hydroxide.</p> <p>Separation of the solid residues (to anaerobic digestion [AD]) and liquid fractions (to filtration).</p> <p>Enzyme hydrolysis using enzymes to break down the sugars in the seaweed.</p>		<p>Acid hydrolysis using hydrochloric acid to break down the sugars in the seaweed. Solid residue outputs are neutralized with sodium hydroxide.</p> <p>Enzymatic hydrolysis is not used.</p>
Conversion / Purification	<p>Liquid fraction from hydrolysis is filtered through nano-filtration membrane with reverse osmosis to remove salts.</p> <p>Fermented using clostridium with additional nutrients added in the form of diammonium phosphate (DAP).</p> <p>Purified through multiple columns and then a molecular sieve. Solid residue (stillage) sent to AD</p>	<p>Purified through a beer column and then three separate product columns. Solid residue (stillage) sent to AD</p>	<p>The slurry from the hydrolysis reactor is separated from the liquid at atmospheric pressure and 50 °C. Undergoes a biphasic reaction in toluene to extract furanics and then purified through filtration. Toluene is recovered for reuse. Hydrogen and butanol added to furanic compounds to create the furanic fuel additive.</p>
Anaerobic Digestion (AD) & process boiler	Organic residues in waste streams are sent to AD to produce biogas for combustion in the process boiler and to supply heat for the process. Excess biogas can be exported as a co-product and digestate used as a fertilizer (considered to be waste residue under RED).		

Allocation method

There are a number of co-products produced from the biofuel production processes, and it is necessary to allocate the environmental impact between them. The co-products include the biofuels, biogas and acetone.

A key objective of this study is to assess the climate change impact of the MacroFuels biofuels against the sustainability criteria identified in the Renewable Energy Directive 2018 (RED). As a result, allocation to the co-products has been made on the basis of energy content, as this is required under RED.

Digestate from anaerobic digestion is considered to be a residue under RED and as a result no allocation or credit has been considered for the digestate. However, digestate potentially represents a useful resource as a fertiliser and soil improver. Consequently, system expansion has been applied in a sensitivity analysis in order to assess the potential benefits of substituting inorganic fertilisers with the digestate.

Results

The production of growing equipment for seaweed cultivation and the hydrolysis step are the main contributors to the environmental impact of MacroFuel biofuel products. In particular, the growing equipment makes a significant contribution to the climate change, particulate matter, acidification, terrestrial eutrophication, marine eutrophication, human toxicity (cancer), photochemical ozone creation and mineral, fossil & renewable resource depletion impact categories. Hydrolysis is particularly significant when considering ozone depletion, human toxicity (non-cancer), freshwater ecotoxicity and freshwater eutrophication.

Within the growing equipment lifecycle stage, the chain used to secure the sheetnets to the anchors and buoys and to keep them underwater accounts for 40% or more of the impact of the growing equipment for all environmental impact categories, except for: human toxicity (cancer effects); freshwater eutrophication; and freshwater ecotoxicity. For these impact categories, the impacts of producing buoys and HDPE pipe account for more than 75% of the impact of the growing equipment.

For ethanol and butanol products, production via acid hydrolysis has a greater impact for 10 out of 13 impact categories, including climate change, than does using enzyme hydrolysis. For the human toxicity (non-cancer effects), marine eutrophication and freshwater ecotoxicity impact categories, the impact of enzyme hydrolysis is greater.

The impact of the production of the furanic fuel additive is lower than ethanol or butanol produced either by the ABE or the EtOH processes for all of the impact categories other than ozone depletion. However, once blended with bio-butanol, the impact per MJ approaches that of the butanol produced via the ABE process (enzyme hydrolysis), as this is the butanol with which it is assumed to be blended.

Benchmarking the MacroFuel biofuels 'cradle to grave' climate change impact for the biofuels against the RED sustainability criteria and other fossil fuel (petrol and diesel) and current biofuel benchmarks (ethanol from sugar beet, ethanol for maize and ethanol from wheat straw) showed the following results:

- None of the baseline MacroFuel biofuels meet the RED sustainability criteria (32.9 g CO₂eq/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 CO₂eq/MJ);
- The 'cradle to grave' climate change impact of all of the baseline MacroFuel biofuels is greater than petrol or diesel; and
- The MacroFuel biofuels all have a significantly greater 'cradle to grave' climate change impact than the bio-ethanol produced from all the comparison bio-feedstocks.

The analysis identified that the baseline MacroFuel biofuels have a greater climate change impact than the bio-ethanol produced from terrestrial-based bio-feedstocks (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-feedstocks on a dry weight basis.

Recommendations and conclusions

Sensitivity analyses were completed in order to identify the effect of key modelling assumptions, to assess variation in the results for alternative scenarios and data and their potential to reduce the climate change impact of the MacroFuel biofuels. These included:

1. Increased seaweed yield;
2. Decreased fuel requirements during seaweed cultivation (seeding and harvesting);
3. Extend growing material lifetimes;
4. Reduced amount of enzyme required in hydrolysis;
5. Maximise recycled content for materials used in growing equipment; and
6. Receiving credit for digestate replacing inorganic fertilisers.

A combined improvement scenario was developed based on assumptions 4, 5 and 6 above. This showed potential reductions in climate change impact by approximately 50% for ethanol and butanol and 59% for the furanic fuel.

Other factors which could reduce the climate change impact of the Macrofuels biofuels include:

- Sequestration of carbon in seaweed in the deep sea;
- Alternative designs for the cultivation system to reduce the amount of chain used;
- Use of CHP in biofuel production; and
- Prioritisation of high value co-products from seaweed in bio-refineries with residues used for energy production.

The improvement options discussed here have the potential to deliver MacroFuel biofuels with significantly lower climate change impact than that of conventional fossil fuels.

When conducting future assessments of pilot or large scale production, it is recommended that primary data are sought for the:

- Manufacturing, use and disposal of growing equipment;
- Operation of machinery during cultivation and harvesting; and
- Supply of materials used in hydrolysis and conversion.

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1 INTRODUCTION

1.1 The MacroFuels Project

The objective of the MacroFuels project is to advance the knowledge base for technologies to produce liquid transportation biofuels from cultivated seaweed (or macroalgae), thereby providing a sustainable solution for the provision of transport fuels. The biofuels targeted as part of the MacroFuels concept are ethanol, butanol, and furanics, suitable as liquid fuels or precursors thereof for use by the heavy goods transport sector and, potentially, 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 rotating crop 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.

1.1.1 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 timespan. They do this without the use of fresh water, fertilizers, pesticides, and farmland, as needed for land-based cultivation. In order to grow, seaweeds need only carbon dioxide (CO₂), sunlight and the nutrients already present in the ocean.

However, this does not necessarily make biofuels from seaweed sustainable. The net benefit of replacing fossil resources by biomass is not sustainable in of itself, simply because biomass is a biogenic and 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 burdens of an environmental, social and economic nature. These may include biodiversity loss or higher environmental and economic costs due to the complexity of, and inefficiencies in, converting biomass to fuel.

Consequently, in order to validate the benefits of any given biofuel concept and, ultimately, to provide a basis for the development of incentivising policies, it is necessary to conduct a comprehensive sustainability assessment. The sustainability assessment that is a part of the MacroFuels project, is a multi-criteria appraisal with the aim of evaluating the impacts of seaweed-derived transport fuels with respect to the environment and society, their technical and economic viability, and health, safety and risk aspects of seaweed biofuel production systems. This report forms part of the sustainability assessment, focusing on environmental impacts in the form of a life cycle assessment (LCA).

1.2 The MacroFuels concept

The objective of the MacroFuels concept is to progress the technologies for producing third generation biofuels from seaweed by assessing current system design concepts. These designs are informed by lab scale testing, field trials and modelling completed within the other work packages of the MacroFuels project. The biofuels production scenarios targeted as part of the MacroFuels concept are ethanol, butanol, and furanics. The technologies employed for their production, the efficiencies achieved, and potential co-products to be used vary, depending on the scenarios chosen.

The LCA evaluates the full value chain and, through that, provides a better understanding of the potential environmental impacts of large-scale cultivation of seaweed and its use as a feedstock for biofuels produced via the following scenarios:

- Bio-ethanol via fermentation;
- Bio-butanol and bioethanol via ABE (acetone, butanol and ethanol) fermentation; and
- Bio-furanics via biphasic reaction with toluene and water, and reaction with bio-butanol and hydrogen.

Bio-ethanol and **bio-butanol** are used as substitutes for petrol. Most cars can use fuel containing up to 10% ethanol, while modified engines can manage blends with up to 85% ethanol. In contrast, blends of 85% butanol can be used in unmodified petrol engines. Additionally, butanol produces more power per litre than ethanol.

Bio-furanics, in contrast, may be used as a fuel additive with diesel when combined with butanol. This means that, in addition to displacing fossil diesel as a fuel, it can also act as a cetane improver to improve the ignition of diesel fuel, with associated improvements in engine performance.

1.3 Renewable Energy Directive (2018/2001/EC)

The Renewable Energy Directive (2018/2001/EC) (the RED) has set a target of 14% of energy for transport to come from renewable sources by 2030. For a biofuel to count towards this target, it must fulfil certain sustainability criteria set out in the RED for greenhouse gas (GHG) emissions and should be identified as no / low risk for additional impacts from indirect land use change. Indirect land use change can increase the net GHG emissions from terrestrial crops used as biofuels, but seaweed is seen as a low risk crop in this context, as it is grown in the sea and will not displace land used to grow food.

The assessment includes an evaluation of the biofuels in the context of the RED sustainability criteria and the benchmarking of the calculated carbon footprints with those of other biofuels and fossil-based

fuels. This will enable the degree to which seaweed-derived fuels classify as sustainable fuels to be established.

1.4 Type and Format of Report

This document is the technical report of the LCA. As such, its structure and content has been guided by the requirements of the international standards on LCA (ISO 14040:2016 and ISO 14044:2016).

The report is structured as follows:

- *Section 2* defines the goal of the study;
- *Section 3* defines the scope of the study;
- *Section 4* outlines the inventory analysis;
- *Section 5* outlines the life cycle assessment;
- *Section 6* outlines the interpretation; and
- *Section 7* outlines the conclusions and recommendations.

The following Annexes are also referenced:

- *Annex A: Environmental impact categories*
- *Annex B: Inventory tables*
- *Annex C: Sensitivity analysis results*
- *Annex D: Seaweed production: 'cradle to gate' impact results*

2 GOAL

The goal of this LCA was to conduct a ‘cradle-to-grave’ assessment of the MacroFuels concept ⁽¹⁾. This will inform future developments by appraising the potential environmental impact of producing biofuels from seaweed for use as transport fuels and contrasting the calculated GHG emissions with reported values for transport fuels produced from other sources.

The LCA is was carried out in accordance with the International Standards for LCA, ISO 14040/14044.

The study has not been subject to a critical review by an external expert.

As a concept study to inform future development, the study is not intended to support comparative assertions.

2.1 Reasons for Carrying Out the Study

The objectives of the LCA are as follows:

1. To increase MacroFuels’ understanding of the life cycle environmental impacts of the biofuels from seaweed concept;
2. Identify where the main environmental impacts occur (the so-called ‘hotspots’) in the full value chain for the production of biofuels from seaweed, in order to support the design of systems for seaweed cultivation and processing to biofuel;
3. Compare the life cycle impacts of the ethanol, butanol and furanic fuels produced; and
4. Benchmark the biofuels assessed under the MacroFuels project against:
 - a. Equivalent conventional, fossil-based, fuels and currently available biofuels; and
 - b. Sustainability criteria for GHG emissions under the Renewable Energy Directive (2018/2001).

2.2 Intended Application and Audience

⁽¹⁾ The technical design of the MacroFuels concept is described in detail in MacroFuels deliverable 6.2 (Dijkstra et al, 2019) *Techno-economic evaluation and health and safety risks*

The intended audience for this report is policy makers and parties interested in understanding the full life cycle environmental impacts of developing processes and design concepts for seaweed cultivation and the production of biofuels from seaweed.

The report is presented in a format that will allow the MacroFuels project to use it in external communications, including the public domain.

3 SCOPE OF THE STUDY

3.1 Product Systems Studied

As outlined in the introduction, the products to be assessed as part of the study are biofuels produced in Northern Europe by the following three seaweed processing scenarios:

- Bioethanol via fermentation (EtOH process);
- Biobutanol and bioethanol via (acetone, butanol and ethanol) fermentation (ABE process); and
- Biofurans via biphasic reaction with toluene and water, and reaction with bio-butanol and hydrogen.

An important step within the EtOH process and the ABE process is the hydrolysis of the seaweed prior to fermentation. This can be completed either by acid hydrolysis or by enzyme hydrolysis and both processes are considered.

The furanic fuel is produced through reaction with butanol and tests have shown it to be suitable for mixing with diesel when blended with butanol in a ratio of approximately 1:9 by weight. For this study, the source of the butanol is assumed to be the biobutanol produced via the ABE process. However, bio-butanol from any source could be blended with the furanic fuel and so the environmental impacts of producing furanic fuel additive without blending with butanol have also been assessed.

The products assessed as part of this study are:

- Ethanol (EtOH process - acid hydrolysis);
- Ethanol (EtOH process - enzyme hydrolysis);
- Ethanol (ABE process - acid hydrolysis);
- Ethanol (ABE process - enzyme hydrolysis);
- Butanol (ABE process - acid hydrolysis);
- Butanol (ABE process - enzyme hydrolysis);
- Furans fuel additive; and
- Furans fuel (10%) / bio-butanol (90%) fuel blend

The furanic fuel additive consists of the following components: furfuryl alcohol (furOH); butyl tetrahydrofurfuryl ether (BTE); and tetrahydrofurfuryl dibutyl acetal (TDA). This mixture can then be blended with butanol.

Further characteristics of these biofuels are shown in *Annex B*.

3.2 Function and Functional Unit

The function of the biofuels products considered in the study is to provide energy for transportation.

The functional unit of the study is therefore defined as:

1 MJ of biofuel used as transport fuel in an internal combustion engine.

This functional unit has been selected as is consistent with the functional unit required to assess the biofuel against the RED sustainability criteria, as outlined in Annex V of the RED.

3.3 System Boundaries

The LCA carried out was 'cradle-to-grave'. This means that all significant life cycle stages associated with the product systems studied were considered, from raw materials, through processing and production, to distribution, use, waste collection, recycling or management of end of life.

Energy and material inputs were traced back to the extraction of resources, and emissions and wastes from each life cycle stage were quantified. *Figure 3-1* shows the boundary of the LCA.

As can be seen from the figure, the following life cycle steps are included within the system boundaries.

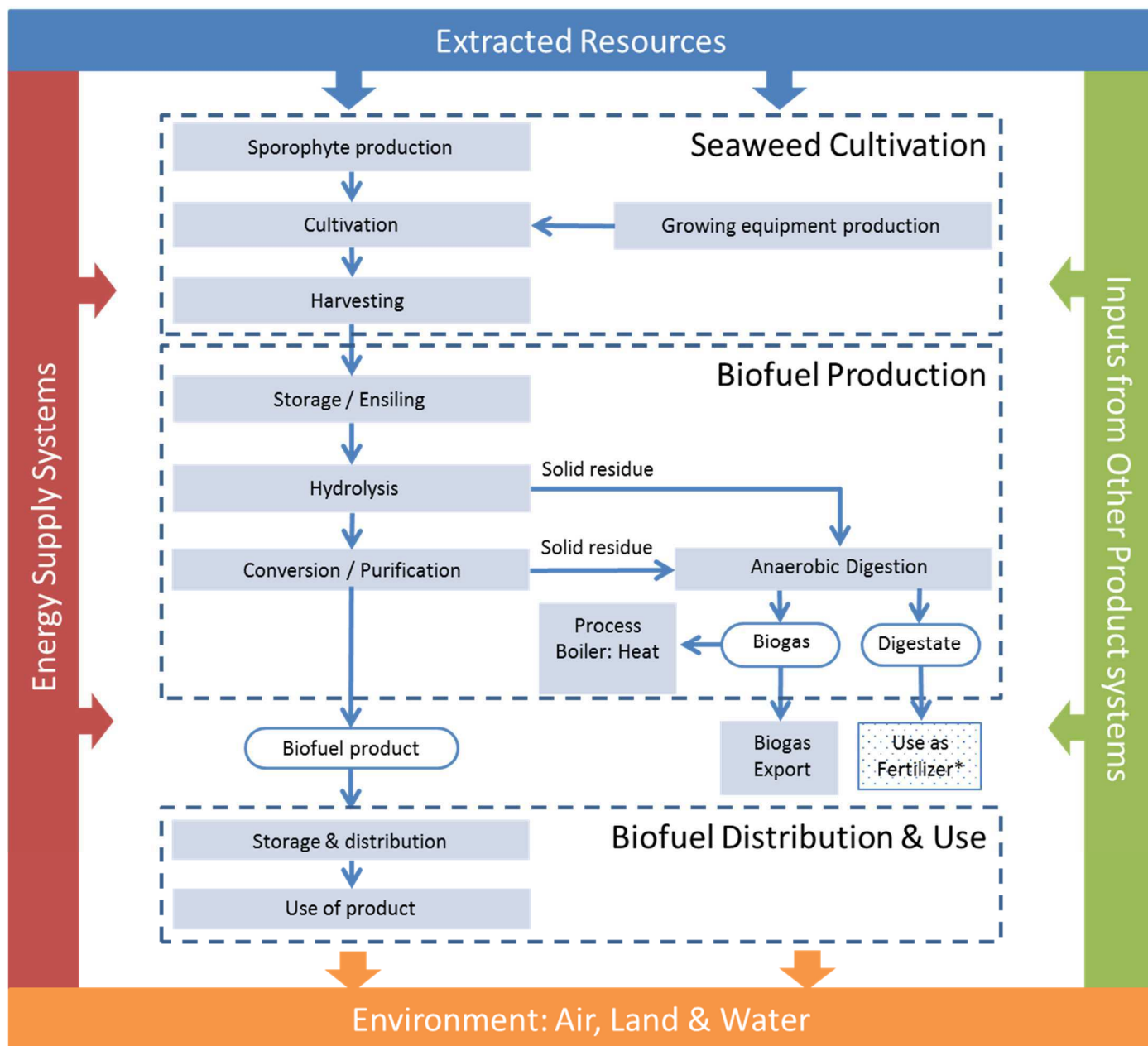
- Growing equipment production – production of all the equipment used in the cultivation of the seaweed.
- Sporophyte production – seedling cultures are raised in dedicated hatcheries, under controlled conditions to produce sporophytes from which seaweed can be grown at sea.
- Cultivation – deployment of sporophyte (seeding) and maintenance of the seaweed (two crops a year).
- Harvesting – mechanical harvesting of seaweed when grown (two harvests a year).
- Storage and ensiling – storing the seaweed and avoiding degradation by ensiling.
- Hydrolysis – breaking down the sugars in the seaweed to give monomeric sugars.
- Conversion / Purification – separating and filtering the sugar mixture from salts and other residues and conversion of monomeric sugars into biofuels, before distilling / blending product mixture as required to yield pure product.
- Anaerobic digestion – solid residues that are produced in hydrolysis and fermentation go to anaerobic digestion to produce biogas that will be used for process heat.
- Process boiler – combustion of biogas to produce heat required for process, with excess biogas able to be sold as a co-product.

- Storage and distribution – storage at the refinery and then distribution and storage at forecourt.
- Use - combustion of the fuel in vehicle internal combustion engines.

3.4 Scenarios

To ensure that the individual assessments are conducted on a common and consistent basis, a number of parameters need to be defined. Some parameters will be the same for all three main scenarios, whilst others will vary. High level parameters have been defined as part of the scenario definition, as outlined in *Table 3-1* below.

Figure 3-1 System boundaries of LCA based on the life cycle of biofuel from seaweed according to the MacroFuels concept



* Digestate residue can be used beneficially as a fertiliser (displacing mineral fertiliser production).

Table 3-1 Parameters defining the three main scenarios for the MacroFuels concept

Parameter	EtOH Process (Ethanol)	ABE Process (Ethanol & butanol)	Furanics process (Furanic fuel)
Seaweed cultivation			
Site	Coastal, 5 km from shore and 50 km from the biorefinery		
Cultivation system	Rotating crop system, two seeding / harvests a year		
Size of field	18,460 ha to produce 1.2 Mtonne DW seaweed per annum (enough to supply biorefinery)		
Growth substrate	Sheetnets with a 30 cm mesh		
Maintenance	Six trips annually		
Harvesting	Twice annually (October and May)		
Harvesting method	Mechanical and automated, achieving 1,000 m² per hour		
Seaweed yield	25 kg(ww) per m² per year (i.e. two harvests at 12.5kg ww per m²)		
Seaweed variety assumed for processing	Brown seaweed (<i>Saccharina latissima</i>)		Red seaweed (<i>Palmaria palmate</i>)
Storage / Conditioning			
Method	Ensiling, for up to 6 months in large onshore tanks		
Hydrolysis			
Method	Hydrolysis (acid or enzymatic)		Hydrolysis (acid)
Residue utilisation	Residue utilised for biogas production (anaerobic digestion)		
Conversion / Purification			
Method	Fermentation, microbiological	Fermentation, microbiological	Biphasic reaction with water-toluene separation and reaction with H ₂ and butanol
Co-Products	Ethanol	Ethanol, butanol and Acetone	Furanics fuel additive or Furanics/butanol fuel blend
Residue utilisation	Residue utilised for biogas production (anaerobic digestion)		
Anaerobic Digestion and Boiler			
Energy	Biogas combusted for heat used in processes		
Co-products	Excess biogas exported and digestate		digestate
Distribution & Use			
Assumptions	300 km distribution transport. Emissions from combustion in internal combustion		

3.5 Dealing with Multi-Functional Processes

A key methodological issue for the assessment is the method for apportioning environmental impacts between product systems. An example of such a process from this study is the ABE process, which produces acetone, butanol, ethanol and biogas. These are all useful co-products from the ABE process and the environmental impact of production needs to be apportioned between them.

The ISO standards on LCA provide a stepwise procedure for the allocation of material and energy flows and environmental emissions when there are interactions between product systems. Preferably, allocation should be avoided, either through increasing the level of detail, or failing this, through system expansion ⁽¹⁾. Where these methods are not applicable, the ISO standard suggests that allocation be undertaken in a way that reflects the physical relationships between the different products or functions (e.g. energy content, mass, economic value, etc.). Rarely will data be sufficient to avoid the need for allocation, and the approaches employed in this study are described below.

3.5.1 Allocation for Co-products

Key objectives of this study are to benchmark the climate change impact of the MacroFuels biofuels against current biofuels and fossil fuels and to assess the biofuels against the sustainability criteria identified in the RED. Therefore, the allocation method for co-products selected for this study has been selected to meet the requirements of the RED.

The RED states that the energy allocation method, as determined by the lower heating value of the co-products, should be used when allocating greenhouse gas emissions to co-products. The RED method does not allow for system expansion to assess the avoided burdens of producing the co-product, other than for the assessment of EC policy, where a comparison using system expansion should be provided.

The RED states that the energy allocation method for co-products is an appropriate method to use, as it is easy to apply, is predictable over time, minimises counter-productive incentives and produces results that are generally comparable with those produced by the substitution method.

Where processing of co-products and/or the fuel is interlinked with feedback loops with earlier steps in the production process (as is the case for all biofuel products considered in the MacoFuels concept), the RED requires that GHG emissions are allocated to the co-products at the refinery level.

⁽¹⁾ System expansion is a method used to avoid co-product allocation. It is based on the principle that the co-product saves, or avoids, provision of another product with equivalent function.

Therefore, all co-products from the same production route assessed in this study have the same environmental impact per MJ of co-product.

The RED also states that wastes and residues should not be treated as co-products and therefore should not have any environmental impact allocated to them. Digestate produced from anaerobic digestion is considered to be a residue under RED and no allocation or credit will be considered for the digestate. However, digestate potentially represents a useful resource as a fertiliser and soil improver and so system expansion will be applied in a sensitivity analysis, in order to assess the potential benefit of inorganic fertilisers assumed to be substituted by the digestate. This is in line with the RED, which states that system expansion should be used as a comparison when assessing policies.

3.6 Allocation for Recycling

In the value chain for the MacroFuels biofuels, the main potential for the use of recycled materials or the recycling of materials at end of life, is for the growing equipment used in seaweed cultivation (e.g. buoys, chains and nets). The assessment assumes that these materials will be recycled where possible at the end of their useful life and explores, through sensitivity analysis, the benefit of using recycled materials for their manufacture.

Typically, these materials will not be recycled into the same products (e.g. the nets are made from PET and may be recycled into PET clothing). As a result, the “recycled content” approach is used for the allocation of the recycling. This means that all impacts incurred from recycling processes are considered to be applied to the system that uses the recycled material, rather than the system that generates the waste for recycling.

3.7 Data and Data Quality Requirements

3.7.1 Data Sources

For the processes included within the system boundaries, all known inputs and outputs were included in the inventory. The MacroFuels concept is not an operating production process. Consequently, specific data for the production of key materials and the main life cycle stages, for which primary data would typically be preferred for LCA of an operational system, are based on literature, lab scale tests / field trials and expert knowledge from partners involved in the MacroFuels project, in order to present a potential system for the production of biofuels from seaweed. The data used are a combination of

specific data developed for the MacroFuels concept and generic (secondary) data. Specific data are ideally sourced for the production of key materials and the main life cycle stages. For the production of energy and materials consumed during processing, and for transport steps, secondary data are used. The data provided by the other deliverables and work packages in the project include harvesting, cultivation and processing of seaweed to biofuel.

Secondary data were sourced from LCI databases such as Ecoinvent 3.0, the GREET model and database¹ and the RED. Data from these sources were used for raw material production, energy production and transport fuel use emissions.

3.7.2 Data Quality Requirements

Data quality requirements are defined in Table 3-2, and are based on the ISO standard on goal and scope definition and inventory analysis.

¹ <https://greet.es.anl.gov/> Argonne National Laboratory, The greenhouse gases, regulated emissions and energy use in transportation model. Accessed May and June 2019.

Table 3-2 Data quality requirements

Parameter	Description	Requirement
Time-related coverage	Desired age of data and the minimum length of time over which data should be collected.	The study is largely hypothetical, based to a large extent on modelled data, for a bio-refinery to be operational in the 2020s. Therefore, the best available current data should be preferred.
Geographical coverage	Area from which data for unit processes should be collected.	Data should be representative of the current European market.
Technology coverage	Technology mix.	Data should be representative of the technology currently available.
Precision	Measure of the variability of the data values for each data category expressed.	Specific and representative data were used in the study. Where there was potential variability in the data, a sensitivity analysis was used to determine its significance.
Completeness	Assessment of whether all relevant input and output data were included for a certain data set.	Specific datasets were benchmarked with literature data and databases. Simple data validation checks (e.g. mass balances) were performed.
Representativeness	Degree to which the data represent the identified time-related, geographical and technological scope.	The data should fulfill the defined time-related, geographical and technological scope.
Consistency	How consistently the study method was applied to different components of the analysis.	The study method was applied to all the components of the analysis.
Reproducibility	Assessment of the method and data, and whether an independent practitioner would be able to reproduce the results.	The information about the method and the data values should allow an independent practitioner to reproduce the results reported in the study.
Sources of the data	Assessment of data sources used.	Data were derived from credible sources and databases.

3.7.3 Cut-Off Criteria

The number of flows in a product system can be considerable. Even simple products can have activities associated with a product system that reach a global scale. As a result, it is necessary for quantitatively irrelevant flows to be 'cut-off' to enable an assessment to be practicably completed. However, caution must be taken so as to not 'cut-off' more flows and related impacts than are acceptable to meet the goal of the assessment.

The ISO standards on LCA suggest using a percentage of total mass, total energy, and total environmental impacts as 'cut-off' criteria (ISO 14044:2006). The criteria employed are as follows.

- a) Mass – if a flow is less than 1% of the total mass of all the inputs and outputs of the biofuel production model, it may be excluded, providing its environmental relevance is not a concern.
- b) Energy – if a flow is less than 1% of the total energy inputs of the biofuel production model, it may be excluded, providing its environmental relevance is not a concern.
- c) Economic / environmental / social relevance – if a flow meets the above criteria for exclusion, yet is considered potentially to have a significant economic / environmental / social impact, it must be included. Material flows that leave the system (products, emissions, waste) and whose environmental impact is greater than 1% of the whole impact of an impact category that is considered in the assessment must be covered. This judgement is made based on experience and documented as necessary.

The sum of the excluded flows must not exceed 5% of mass, energy or environmental relevance.

3.8 Modelling Methods, Impact Methods and Impact Categories Used

The LCA model is developed in the SimaPro 8.5.2.0 LCA software developed by PRé consultants. SimaPro is used extensively within the LCA community and contains a large database of processes (including Ecoinvent 3.4 and ELCD) and all the impact assessment methods required in this study.

The impact assessment considered the following environmental categories:

- Climate change;
- Ozone depletion;
- Human toxicity, cancer effects;
- Human toxicity, non-cancer effects;
- Particulate matter;
- Photochemical ozone formation;
- Acidification;

- Terrestrial eutrophication;
- Freshwater eutrophication;
- Marine eutrophication;
- Freshwater ecotoxicity;
- Water resource depletion; and
- Mineral, fossil & renewable resource depletion.

The European Commission-developed International Reference Life Cycle Data System (ILCD) impact assessment method (version 1.0.9, May 2016) is used to assess all the above environmental impacts. This is because:

- it offers a consistent and scientifically accepted set of characterisation methods for the breadth of environmental impacts;
- it has a track record of use by the LCA community and governments globally;
- it is justified by peer review publications and detailed scientific supporting material;
- it conforms to the ISO standards for LCA; and
- global warming potentials for carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are the same as those specified in the RED and so facilitate comparison with benchmarks outlined with RED.

Full descriptions of each of the impact categories is provided in *Annex A*.

3.9 Renewable Energy Directive (RED): GHG Emissions Calculation and Sustainability Criteria

In the context of biofuels and the European Union, a method for calculating biofuel GHG emissions values is laid out in the RED.

The method for calculating the GHG emissions associated with biofuels is provided in Annex V of the RED and the communication from the EU on the practical implementation of the EU biofuels and bioliquids scheme (2010/C 160/02). This states that GHG emissions from the production and use of transport fuels, biofuels and bioliquids are to be calculated as shown in the equation below. Not all parameters are relevant when considering seaweed, and the equation can therefore be shortened as indicated.

$$\begin{aligned}
 E &= e_{ex} + e_i + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \\
 &= e_{ex} + e_p + e_{td} + e_u - e_{ccs}
 \end{aligned}$$

Where:

E	=	total emissions from the use of the fuel;
e_{ex}	=	emissions from the extraction or cultivation of raw materials;
e_i	=	annualised emissions from carbon stock changes caused by land-use change;
e_p	=	emissions from processing;
e_{td}	=	emissions from transport and distribution;
e_u	=	emissions from the fuel in use;
e_{sca}	=	emission saving from soil carbon accumulation via improved agricultural management;
e_{ccs}	=	emission saving from carbon capture and geological storage;
e_{ccr}	=	emission saving from carbon capture and replacement; and
e_{ee}	=	emission saving from excess electricity from cogeneration.

In order to contribute to the RED target for 14% of energy used in the transport sector to be from renewable sources by 2030, biofuels are required to fulfil certain sustainability criteria. These include a 65% GHG emission saving from the use of the biofuel compared to the comparable fossil fuel for biofuels used for transport produced in installations which begin operation after 1 January 2021. The GHG emission saving from biofuel is calculated as:

$$SAVING = (E_F - E_B) / E_F$$

Where:

E_B	=	total emissions from the biofuel or bioliquid; and
E_F	=	total emissions from the fossil fuel comparator.

For biofuels, for the purposes of the calculation referred to above, the fossil fuel comparator E_F is 94 g CO₂eq/MJ.

3.10 Assumptions and Limitations

Where specific data were not available and estimates or assumptions were applied, these are clearly described and specified in this report. Where the estimates or assumptions are found to have a significant influence on the overall environmental profile, their influence is further investigated in the sensitivity analysis. The main assumptions in this study are as follows:

- Data for the ABE process, using enzyme hydrolysis have been assumed to be the same as the acid hydrolysis route for all process steps other than the hydrolysis process step; and
- Exclusion of capital burdens for infrastructure where the equipment / infrastructure is assumed to have a lifetime of greater than 20 years.

The main limitation of this study is that the MacroFuels concept does not represent actual operational systems for the production of seaweed and biofuels for the types of systems and scales considered. All data characterising the potential system for the production of biofuels from seaweed are based on literature, lab scale tests and relatively small scale field trials. This places limitations on the technological representativeness of a future system and the temporal validity of the study. These limitations are mitigated as far as possible by use of data and assumptions based on current technologies and trends identified through the scaling up the findings from other research and modelling activities completed as part of the MacroFuels project.

3.11 Interpretation of Results

The interpretation phase of the study identifies significant issues based on the results and evaluates these considering completeness, sensitivity, and consistency. Conclusions, limitations and recommendations are then drawn.

The issues considered as part of the interpretation phase include:

- Identification of the significant environmental impacts ('hotspots') within the value chain of the biofuel products assessed;
- Sensitivity analysis to investigate key contributions or uncertainties in the assessment; and
- Benchmarking the climate change impact (i.e. GHG emissions across the value chain) of the biofuel products against:
 - Equivalent conventional, fossil-based, fuels and currently available biofuel; and
 - Sustainability criteria for GHG emissions under the Renewable Energy Directive (2018/2001).



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4 LIFE CYCLE INVENTORY (LCI) ANALYSIS

This chapter describes the data collection process, as well as the assumptions applied. It also provides an overview of the each life cycle stage involved in generating biofuel from seaweed within the scope of the MacroFuels concept, as outlined in *Figure 3-1*. All inventory data for seaweed cultivation, processing seaweed to biofuel and use of the biofuels are presented in *Annex B* (Inventory tables).

The biofuels targeted as part of the MacroFuels project are ethanol, butanol, and furanics. The technologies employed for their production, the efficiencies achieved, and potential co-products to be used vary, depending on the value chain chosen. A scenario approach has been employed to accommodate this potential for variation.

4.1 Seaweed Cultivation

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 (*Alaria esculanta*, *Fucus vesiculosus*, *Saccharina latissima*, *Saccorhiza polyschides*), three red (*Gracilaria vermiculophylla*, *Palmaria palmata*, *Porphyra umbilicalis*), and one green (*Ulva lactuca*) seaweed species. They have been chosen in order to cover a range of seaweeds, all common in European coastal waters, and each with their distinct compositions.

For the purposes of assessing the hypothetical biorefinery considered in the MacroFuels concept, this 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 seaweed compositions used for in the modelling for brown seaweed and red seaweed are detailed in *Table 4-1*.

Table 4-1 Model components and seaweed composition (dry weight basis)

Model component	Model component formula	Brown seaweed (EtOH & ABE) wt _{dw} %	Red seaweed (Furanics) wt _{dw} %
Glucose	C ₆ H ₁₀ O ₆	16.21	5.0
Xylose	C ₅ H ₁₀ O ₅	0.48	36
Galactose	C ₆ H ₁₂ O ₆	0.70	15
Fucose	C ₆ H ₁₂ O ₅	2.37	0.0
Rhamnose	C ₆ H ₁₂ O ₅	0.00	0.0
Glycerol	C ₃ H ₈ O ₃	0.55	7.0
Mannitol	C ₆ H ₁₄ O ₆	16.35	0.0
Galacturonic acid	C ₆ H ₁₀ O ₇	0.70	0.0
Guluronic acid	C ₆ H ₁₀ O ₇	4.44	0.0
Glucuronic acid	C ₆ H ₁₀ O ₇	1.10	0.0
Mannuronic acid	C ₆ H ₁₀ O ₇	9.02	0.0
Iduronic acid	C ₆ H ₁₀ O ₇	0.00	0.0
Protein	C ₆ H ₁₄ N ₂ O ₂	2.62	15
Protein insoluble	C ₆ H ₁₄ N ₂ O ₂	2.62	0.0
Other water-soluble organics	C ₁₂ H ₂₂ O ₁₁	9.13	0.0
Water insoluble organics	C ₂₂ H ₄₄ O ₂	9.13	0.0
Sulphate	SO ₄ ²⁻	2.88	0.0
Other org sulph comp	C ₅ H ₁₁ NO ₂ S	0.96	0.0
Other org sulph comp solid	C ₅ H ₁₁ NO ₂ S	0.96	0.0
Ca ²⁺	Ca ²⁺	1.56	0.5
K ⁺	K ⁺	4.46	4.7
Na ⁺	Na ⁺	3.37	1.9
Other anions	Cl ⁻	9.88	8.1
CaCO ₃	CaCO ₃	0.43	0.0
Other insoluble ash	SiO ₂	0.06	0.0
Other soluble ash	Mg ₃ (PO ₄) ₂	0.05	6.8
Total		100	100

4.1.1 Sporophyte Production

Seaweed reproductive material (sorus) is obtained from mature fertile seaweed. In the hatchery, from the sorus, male and female zoospores are released. After germination, they develop to gametophytes that produce eggs and spermatozooids. Following fertilisation, diploid sporophytes are produced that develop into juvenile sporophytes, or seedlings. The cells of the juvenile sporophyte differentiate at an early stage, with rhizoid-like cells becoming the holdfast via which the sporophytes attach themselves to a suitable substrate.

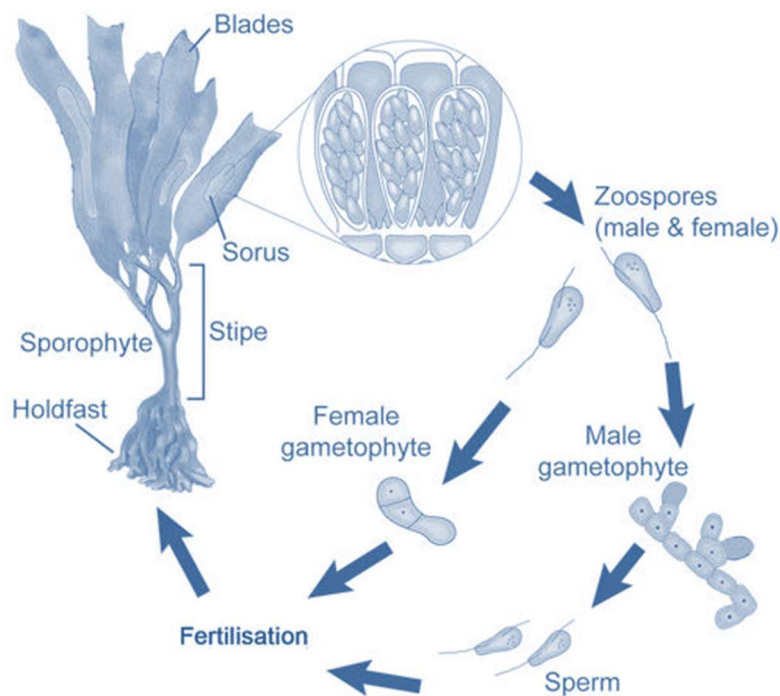


Figure 4-1 Generic life cycle of seaweed

Seedling cultures are produced in dedicated hatcheries. Under controlled conditions, these ensure the release of spores from collected fertile seaweed.

Sporophyte production was not a part of the MacroFuels project. As such, data for its production have been estimated from literature (Fry *et al*, 2012).

4.1.2 Growing Design / Equipment for Seaweed Cultivation

The design of the seaweed cultivation system was based on a concept published in open literature (Groenendaal, Vandendaele, & Vroman, 2017; Sioen, 2015). The system is built from segments. The design of one segment is depicted in *Figure 4-2*. Each segment consists of 8 sheetnets of 11.5x3.2 m, bringing the total effective area to 92x3.2 m². The segments are connected to grids, with (shared) anchors and buoys.

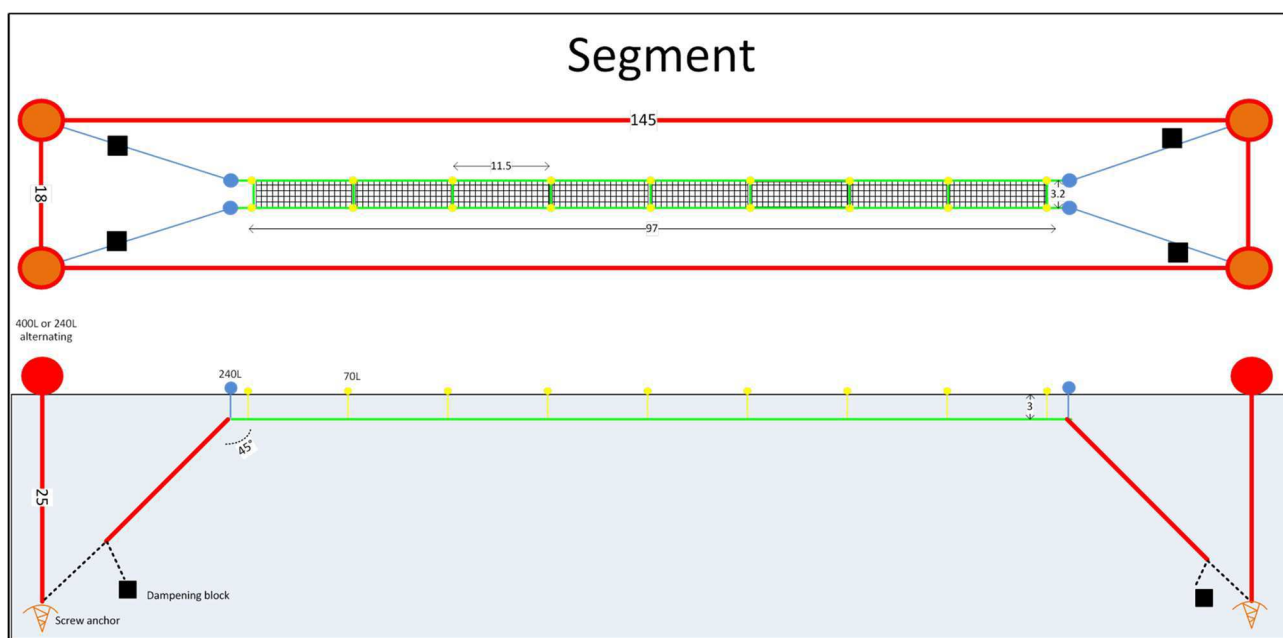


Figure 4-2 Design of the segments of the grow-out cultivation system

The principal materials required for building the cultivation system include the following.

- **Sheetnets:** 30 cm mesh net made from polyester non-woven material.
- **Chain (10mm) & PE tubing (110mm diameter):** galvanised steel chains are used to hold the nets in place and to connect to the buoys and dampening blocks. About 70% of the amount of required chain is chain inside the PE tubing. This chain is placed into the PE-tubing to provide enough weight to prevent the sheetnets and the seaweed from floating, and to provide enough strength to the segment to survive the harsh environment at sea during storms.
- **Buoys:** heavy duty buoys are required to operate in the open ocean.
- **Screw anchors and dampening blocks:** galvanised steel screw anchors and concrete dampening blocks to hold the segments in place.

The inventory table detailing the growing equipment used in the system considered by MacroFuels can be seen in *Table 4.2* below and in *Annex B* (Inventory data).

Table 4-2 Growing equipment required for MacroFuels seaweed cultivation system

Component	Unit	amount per hectare	Total weight per tonne seaweed (kg ww)	Lifetime (years) ⁽¹⁾
Sheetnets	no.	272	4.00	5
Buoys (incl. marker buoys)	no.	679	32.6	10
Chain 10mm	Metres	9680	73.6	5
Hooks and shackles	no.	1495	3.65	10
Dampening blocks	no.	136	299	10
Screw anchor	no.	72	28.9	10
Tubing (incl. spreader bars)	Metres	7840	54.9	10

The segments described above are then placed into grids of three segments. Within a grid, the segments share anchors, mooring lines and buoys. Grids are placed into fields with space (18 m) between the grids allowing for boat movement and manoeuvre.

The grow-out system is considered to be built in two parts: one being the sheetnet assembly; and the other being construction of the structural base. The structural base assembly consists of anchors, blocks and marker buoys and serves as the base onto which the sheetnets are connected. The structural base part is assembled offshore at the location of the seaweed field, using a multifunctional platform vessel. The screw anchors are installed by the same vessel using a drill-like installation.

The sheetnet assembly consists of sheetnets, chains tubing and buoys. The sheetnet parts of the segment are assembled onshore and then each segment is individually towed, by tug boat, to the final destination at the seaweed field. Once in position, the segment is attached to the structural base.

The complete cultivation system is sized to produce 1.2 Mtonne DW seaweed per year. The system is based on growing two crops (brown and green seaweed) in sequence, with an average yield of 25 kg/m² (effective area) total. This results in a cultivation field with an effective area of approximately 18,460 ha for two harvests a year. This is a quite substantial area and would most likely need to be

⁽¹⁾ Personal communication with Bert Groenendaal, SIOEN, May 2019.

divided into separate fields. The average distance from the cultivation field to the biorefinery is assumed to be 50km.

4.1.3 Cultivation: Seeding and Maintenance

Following the production of the sporophytes, the cultivation of the feedstock seaweed comprises the seeding of the sporophytes onto substrate at sea (sheetnets), cultivation, and harvesting.

A mixture of sporophytes and binding agent is taken from the hatcheries and transported to the sheetnets by boat. The sporophytes are then sprayed onto the substrate (sheetnets) offshore at the field. A seeding machine is used that comprises a cleaning part, a pressing part, a seeding part and a second pressing part. The seeding machines can be used for both annual crops during the total lifespan of the field, are modular units that can be placed onto a ship. The cleaning part cleans the nets before the sporophytes are deployed. The pressing part removes water from the sheetnets. The seeding part deploys the sporophytes and binding agent. The second pressing part presses the sporophytes into the sheetnets before the sheetnet is lowered into the water. Seeding conditions (e.g. wave height, temperature and wind speed) are considered on average equal for both crops/periods and for all fields. Details on the seeding machine equipment and fuel requirements are shown in Table 4-3. The seeding machinery has not yet been developed and so operation speeds and fuel requirements for machine have been estimated based on expert judgement.

Table 4-3 Seeding machine equipment data

	Quantity	Units
Seeding machine weight	12,000	Kg
Seeding speed	434	m ² /hr
Machine fuel use	10	L/hr

Maintenance of the deployed segments and field occurs throughout the year. When the seaweed is deployed/growing the maintenance includes checking, refastening, and removal of waste etc. Because offshore operation maintenance is expensive (Burg, Duijn, Bartelings, Krimpen, & Poelman, 2016), maintenance is limited to checking and refastening between the seasons, e.g. after storms. Growth of mussels and undesired biomass is limited to excessive growth at critical places only. The harvesting and seeding both include a cleaning step, cleaning between seasons is therefore not necessary. For the MacroFuels case, the details of the maintenance trips taken and associated data are presented in Table 4-4.

Table 4-4 Maintenance trip data for MacroFuels to observe seaweed cultivation field

	Quantity	Units
Maintenance trips per year	6	#
Area covered per trip (by each boat)	200	Ha
Travel between different growing areas per trip	100	Km
Machine fuel use	3	L/km

No addition of nutrients will take place. Although higher yields are seen where nutrients are added, this is considered not 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.

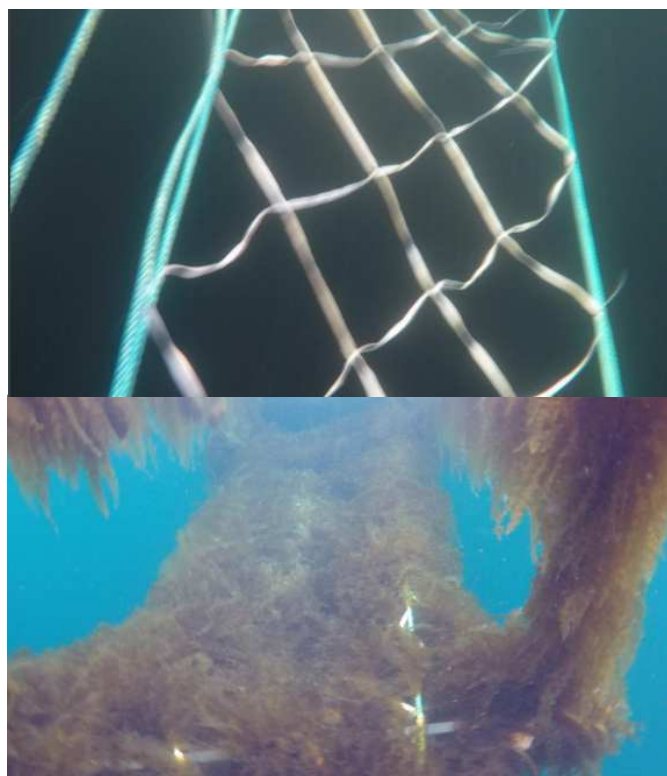


Figure 4-3 Sheetnet (AlgaeNet) – newly deployed and with seaweed growth

4.1.4 Harvesting

The cultivation system is designed to enable seaweed crop rotation for two harvests per year, with harvests in May and October. The hourly capacity of the harvesters has been set equal to the MacroFuels project objective of 1,000 m²/hr effective area. Harvesting machines / platforms are transported by barge to the seaweed cultivation field for each harvest. To prevent spoilage, the seaweed must be processed (dried, ensiled) within 24 hrs of harvesting. The time required to bring the harvested seaweed to the refinery limits the time available for harvesting. The distance from the field to the refinery is anticipated to be 50 km. *Table 4-5* details the data for the harvesting of the grow-out system in the MacroFuels case. The harvesting machinery has not yet been fully developed and so operation speeds and fuel requirements for machine have been estimated based on expert judgement through comparison to agricultural / forestry equipment of a similar size.

Table 4-5 Harvesting of seaweed from cultivation field

	Quantity	Units
Machine weight	12,000	Kg
Harvesting speed	1000	m ² /hr
Machine fuel use	10	L/hr

4.2 Processing Seaweed to Biofuel

The biorefinery design is assumed to have a processing capacity of 1.2 Mtonne seaweed (dw) per year, as this equivalent to that of an existing large bioethanol plant in the port of Rotterdam, the Netherlands.

The data for processing seaweed to biofuel have been sourced from MacroFuels deliverable 6.2, *Techno-economic Evaluation and Health and Safety Risk Assessment*. The processing data were generated using the Aspen Plus 10.0 software. Thermodynamic data was taken from the Aspen Plus database, NREL data base and NIST database (accessed through Aspen Plus). All of the data for each of the MacroFuel biofuel production scenarios are provided in *Annex B* (inventory data).

The biorefinery was modelled as a steady-state continuous process. Batch-operations were represented as a continuous process by averaging annual throughput over 8000 hours of operation.

Key assumptions in the modelling include:

- Constant fresh seaweed composition, variation assessed in a separate sensitivity study;
- Constant conversion in ensilage;
- Absence of heat losses to the environment; and

- Absence of pressure drop in heat exchangers, mixers and reactors.

Fejl! Henvisningskilde ikke fundet. Table 4-6 provides an overview of the biofuel production process for each biofuel scenario. Figure 4-4 and Figure 4-5 show process diagrams for bio-ethanol/ABE and bio-furanics production, respectively.

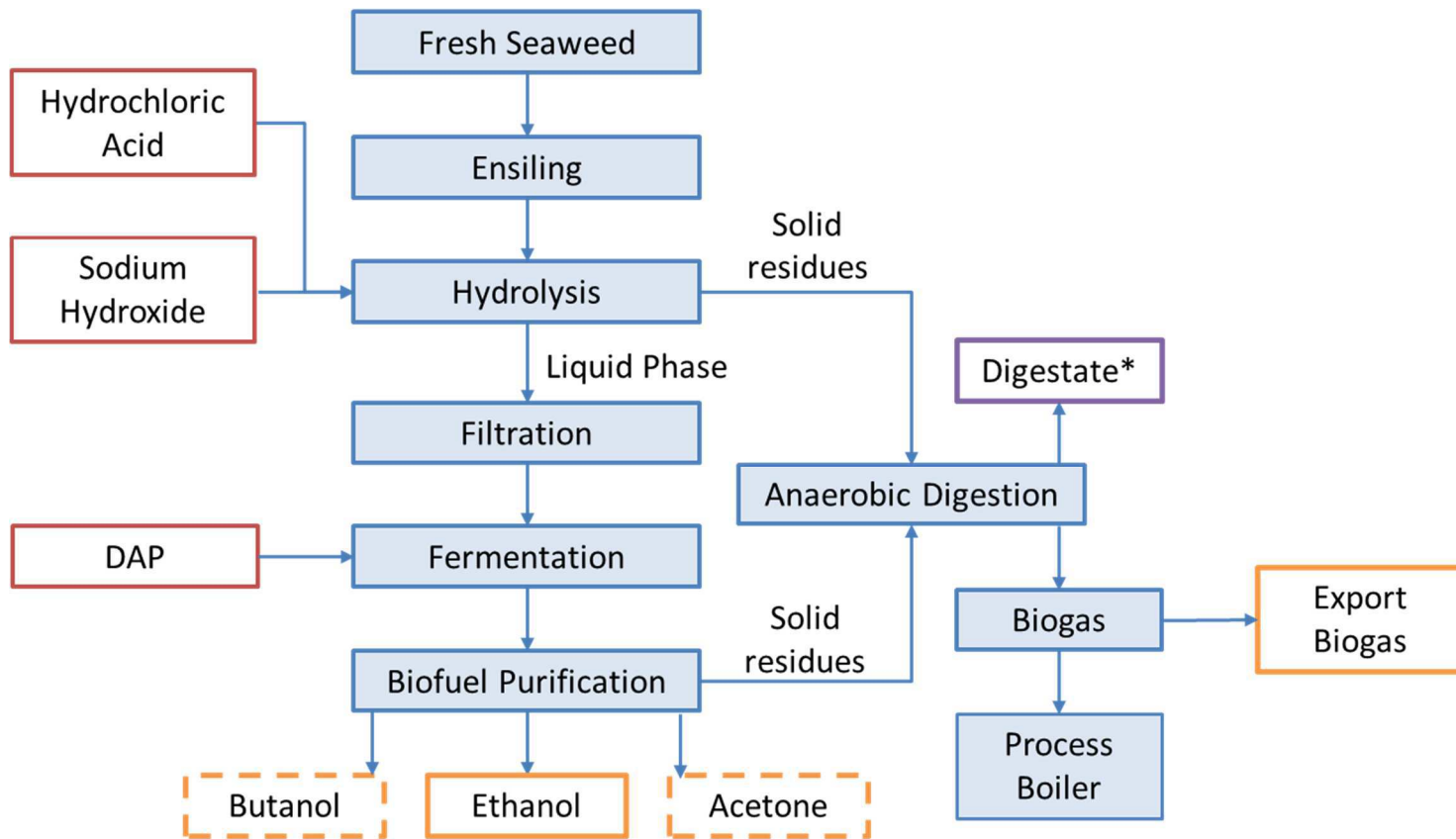
Table 4-6 an overview of the biofuel production process for each biofuel scenario

Process Stage	EtOH process	ABE process	Furanic fuel
Storage / Ensiling	Seaweed ensiled using LAB to prevent seaweed degradation		
Hydrolysis (Acid or Enzymatic)	Acid hydrolysis using hydrochloric acid to break down the sugars in the seaweed. The residual acid is neutralized with sodium hydroxide.		Acid hydrolysis using hydrochloric acid to break down the sugars in the seaweed. Solid residue outputs are neutralized with sodium hydroxide.
	Separation of the solid residues (to AD) and liquid fractions (to filtration).		
	Enzyme hydrolysis using enzymes to break down the sugars in the seaweed.		Enzymatic hydrolysis is not used.
Conversion / Purification	Liquid fraction from hydrolysis is filtered through nano-filtration membrane with reverse osmosis to remove salts.		The slurry from the hydrolysis reactor is separated from the liquid at atmospheric pressure and 50 °C.
	Fermented using clostridium with additional nutrients added in the form of diammonium phosphate (DAP).		Undergoes a biphasic reaction in toluene to extract furanics and then purified through filtration. Toluene is recovered for reuse. Hydrogen and

	Purified through multiple columns and then a molecular sieve. Solid residue (stillage) sent to AD	Purified through a beer column and then three separate product columns. Solid residue (stillage) sent to AD	butanol added to furanic compounds to create the furanic fuel additive.
Anaerobic Digestion (AD) & process boiler	Organic residues in waste streams sent to AD produces biogas for combustion in the process boiler to produce heat for the process. Excess biogas can be exported as a co-product and the digestate used as fertilizer (considered to be waste residue under RED).		

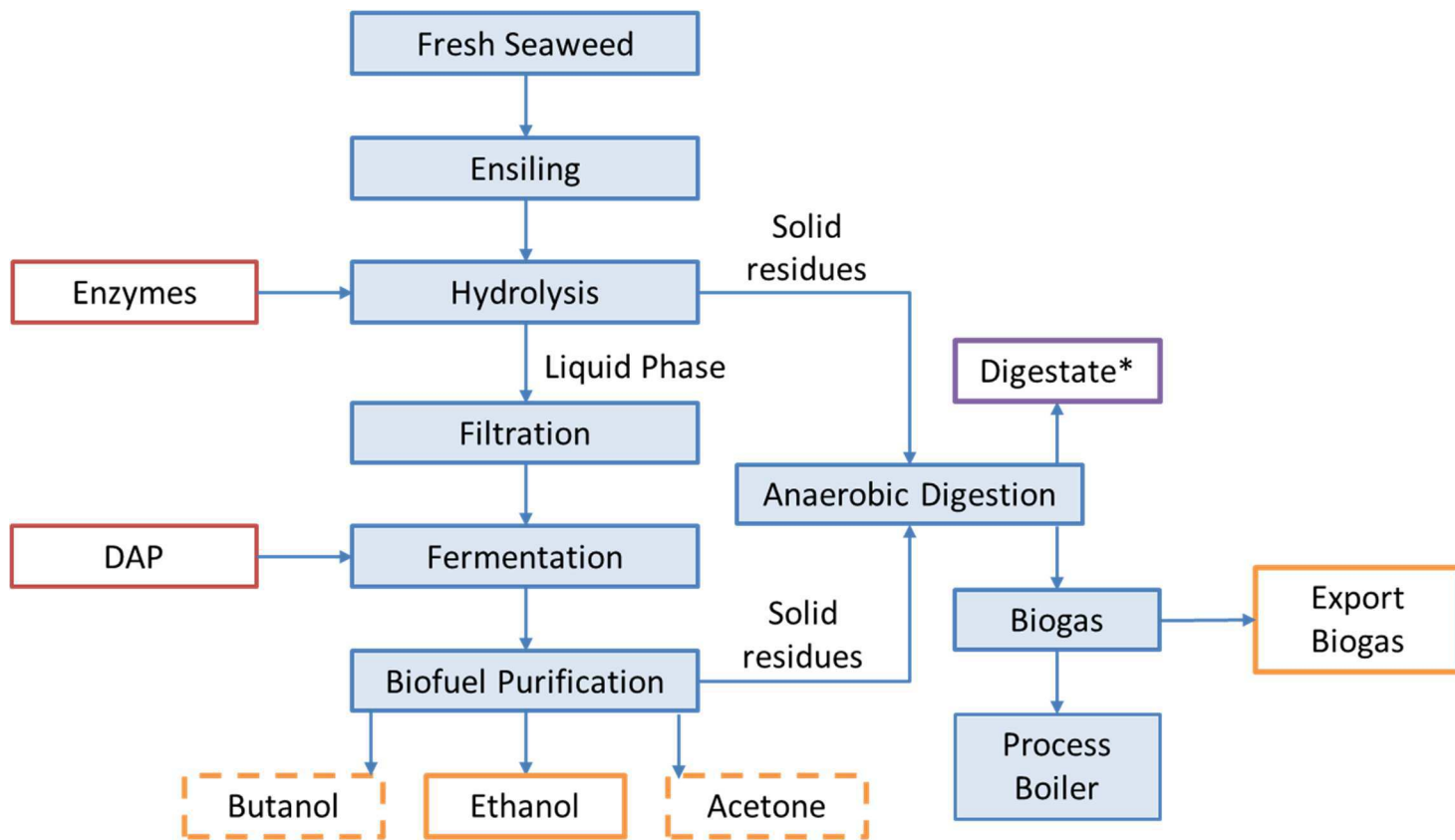
Figure 4-4: process diagrams of bio-ethanol and bio-ABE production acid hydrolysis, A, and enzyme hydrolysis, B.

A- Acid hydrolysis



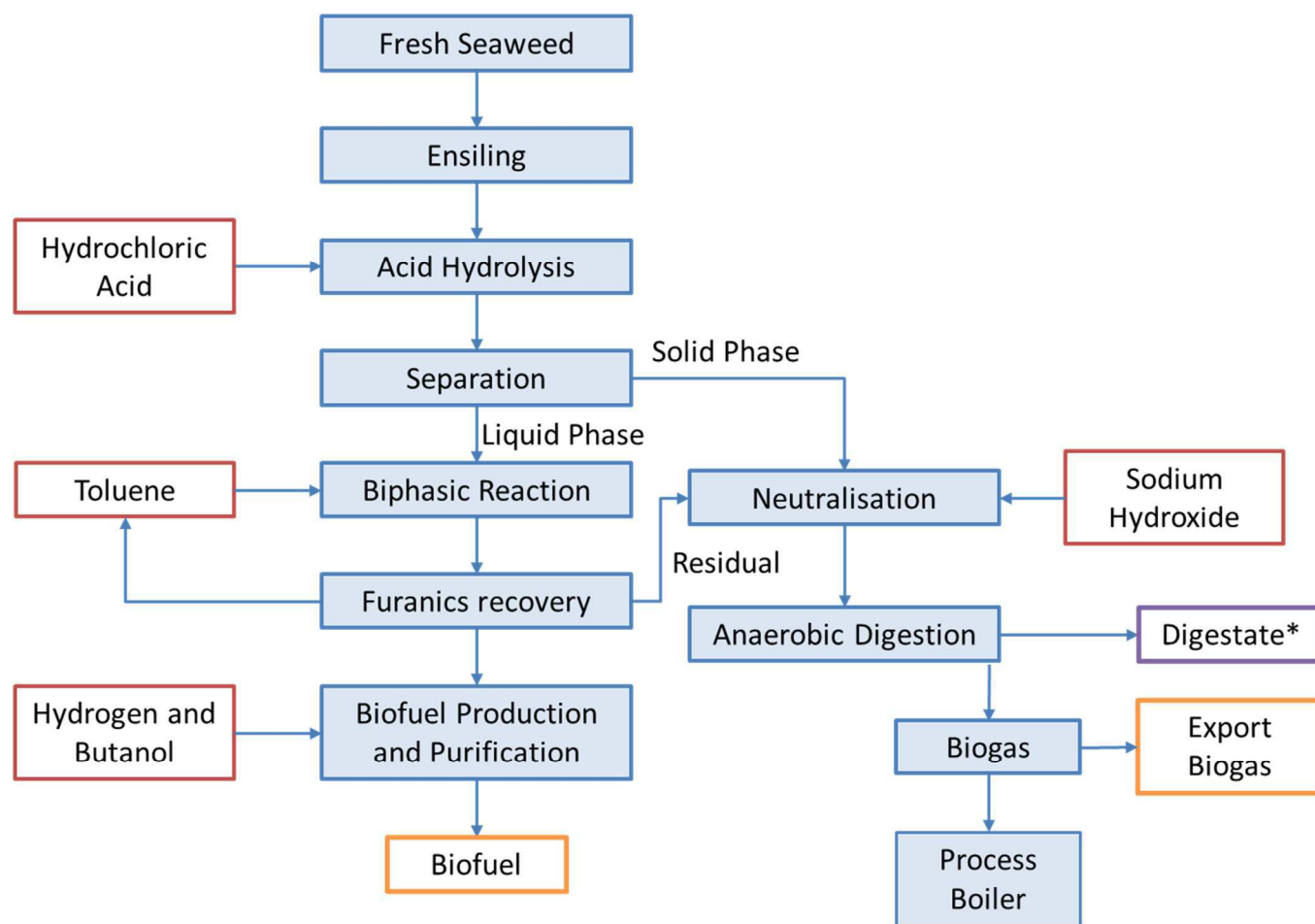
*Digestate treated as a waste stream

B- Enzyme hydrolysis



*Digestate treated as a waste stream

Figure 4-5: process diagram of bio-furanics production



*Digestate treated as a waste stream

4.2.1 Storage / Ensiling

Since biofuel production at large scale will need to operate as a continuous process with year-round supply of feedstock, there is a need to preserve the seaweed biomass that is harvested. The purpose is to minimise the degradation of the seaweed and the loss of organic matter. This is done by adding lactic acid bacteria (LAB) to the seaweed, such that the sugars present are converted to lactic acid by an anaerobic fermentation process. Due to a drop in pH caused by the lactic acid and the absence of oxygen, LAB growth will be dominant, inhibiting the growth of other microorganisms such as bacteria, yeasts and fungi that would degrade the seaweed. The ensiling process will cause a 0.003% mass loss in the fresh seaweed, with this mass vented to air as H_2 , CO_2 and water.

The ensiling storage vessels, assumed to be located onshore, need to have a large volume to allow the biorefinery to run all year round.

Storage and ensiling of harvested seaweed at sea in large plastic containers (for up to 6 weeks), prior to storage on land, has also been considered in the MacroFuels project in a sensitivity analysis. This could provide more flexibility in harvesting operations, with potential cost reductions for transportation of harvested seaweed to the bio-refinery.

The storage / ensiling process is assumed to be the same for all processing scenarios. The production of LAB has been excluded from the life cycle inventory, as only small amounts will be required (<1% of processed biomass).

4.2.2 Hydrolysis

Hydrolysis is the process of breaking down the carbohydrates in seaweed to give monomeric sugars in the liquid phase that are suitable for fermentation or thermochemical conversion into biofuels. Two options for hydrolysis are considered: acid hydrolysis; and enzyme hydrolysis.

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.

4.2.2.1 EtOH Process & ABE Process

For EtOH and ABE, both enzymatic and acid hydrolysis were assessed and compared. Acid hydrolysis requires any products to be neutralized with a base. In this case, the acid used is hydrochloric acid (HCl) and the base used is sodium hydroxide (NaOH). Both HCl and NaOH were assumed to be produced in Europe with an average European production mix.

For the enzyme hydrolysis, the enzymes were assumed to be cellulase enzymes produced externally to the site with a loading of 10g enzyme / kg seaweed (dw). This value was selected based on lab scale tests conducted as part as the MacroFuels project (MacroFuels D2.4, 2019) and is similar to values found in literature for the use of cellulase enzymes in the production of bio-ethanol (MacLean & Spatari, 2009).

4.2.2.2 Furanics Process

Only acid hydrolysis using HCl and NaOH was assessed for the furanics process. The solid residues from the hydrolysis reactor are separated from the liquid at atmospheric pressure at 50°C using filters and centrifuges.

4.2.3 Conversion / Purification

The filtered liquid hydrolysate mixture is converted to biofuel either by fermentation (EtOH and ABE processes) or using a biphasic reaction (furanics process).

4.2.3.1 EtOH Process & ABE Process

For the ethanol and ABE processes, the liquid phase from hydrolysis is first filtered through a nanofiltration membrane, with reverse osmosis to remove salts, which may inhibit fermentation, and to yield a conditioned hydrolysate. The filtered liquid hydrolysate is then fermented by clostridium (CLOST) with additional nutrients added in the form of diammonium phosphate (DAP), to give a mixture containing acetone, butanol and ethanol for the ABE scenario, and only ethanol from the EtOH process scenario.

For ABE purification, the liquid output from fermentation is initially separated in a beer column, to separate stillage (liquid / solid residues) which are sent to the anaerobic digester. Subsequently, the separate sections are further purified in a further three condenser columns to produce separate pure outputs of acetone, butanol and ethanol products, residual wastewater and a small amount of vented gas.

For EtOH purification, the liquid output from fermentation is first fed through a CO₂ stripper to remove CO₂. It then goes through a beer column where the stillage (liquid / solid residues) is separated, to be fed into the anaerobic digester. The ethanol-rich liquid fraction is then passed through additional columns and a molecular sieve to separate the pure product from the residual wastewater.

The production of CLOST has been excluded from the life cycle inventory, as it is assumed that it will be recovered from the process, with only small amounts of externally produced CLOST required (<1% of processed biomass).

4.2.3.2 Furanics Process

For the furanics scenario, the hydrolysed liquid phase is concentrated by removing 50% of the water via a reverse osmosis membrane. The hydrolysate then undergoes a biphasic reaction in water and toluene. Toluene is added to the aqueous phase with a 1:1 volume ratio. The reactions take place at a temperature of 130°C (autogenous pressure) for 120 minutes. Monomeric sugars in the solution are converted to furfural, hydroxymethylfurfural (HMF) and levulinic acid (Lev-A) in the biphasic reactor. These products are preferentially dissolved to the toluene and separated from the water. The furanic products are then separated from the toluene and the toluene is recovered for re-use. The extracted furfural and HMF are converted into the furanics fuel by adding butanol and bubbling hydrogen gas through the mixture prior to concentration by distillation. An excess of butanol is used to create the furanics/butanol blend. The butanol used in this process is assumed to be the biobutanol produced from seaweed via the ABE process. The compounds which make up the furanic fuel additive produced are as follows:

- 2-methyltetrahydrofuran ($C_5H_{10}O$);
- Furfuryl alcohol ($C_5H_6O_2$);
- Butyl tetrahydrofurfuryl ether ($C_9H_{18}O_2$);
- Tetrahydrofurfuryl dibutyl acetal ($C_{14}H_{28}O_4$); and
- Other non-identified components soluble in butanol.

4.2.4 Anaerobic Digestion & Process Boiler

Anaerobic digestion (AD) is used to convert the solids residues from hydrolysis and conversion / purification to biofuel into biogas. The biogas is used as a fuel to meet the heat demand of the process. Excess raw biogas can be exported if it is not all required to supply heat. Ensiled seaweed can be added if additional heat production is required. Excess biogas from the EtOH and ABE processes is assumed to be exported for use by other users in the local area. The biogas is treated as a co-product and environmental burdens are allocated to all co-products based on energy content (in line with the requirements of the RED). For the furanics scenarios, all of the biogas produced is required to provide process heat and so no biogas is exported as a co-product.

The digestate waste produced through AD can be used as a fertilizer because of its nitrogen, phosphorous and potassium content. In the baseline scenario, digestate is considered to be a waste residue in line with the RED sustainability criteria method. A similar process is used for the EtOH, ABE and furanics processes.

4.3 Storage & Distribution

This covers the transport from the refinery to the forecourt. Data characterising this life cycle stage follow the assumptions used in the Biograce project¹. The distribution assumption is that fuel travels by truck 150km from refinery to depot and then 150km from depot to forecourt. Assumptions for storage include electricity demand at the fuel depot and the filling station. The electricity demand is 0.84 kJ electricity per MJ of fuel stored at the depot; and 3.4 kJ of electricity per MJ of fuel at filling stations.

¹ BioGrace Excel tool version 4d for Renewable Energy Directive (2009/28/EC, RED)

4.4 Use

The scope of the ‘cradle to grave’ assessment of the biofuels requires the assessment of the biofuels use in an internal combustion engine. Emissions associated with each of the fuels have been modelled using data from the GREET model¹. Details of the emissions to air associated with each of the products are shown in *Annex B*. No data are available for the combustion of the furanic fuel, and so emissions data for butanol have been used as a proxy.

¹ <https://greet.es.anl.gov/> Argonne National Laboratory, The greenhouse gases, regulated emissions and energy use in transportation model. Accessed May and June 2019.

5 LIFE CYCLE IMPACT ASSESSMENT

This chapter presents the results of the study for each impact category considered. The results for the products from the three different processing routes are compared for each impact category.

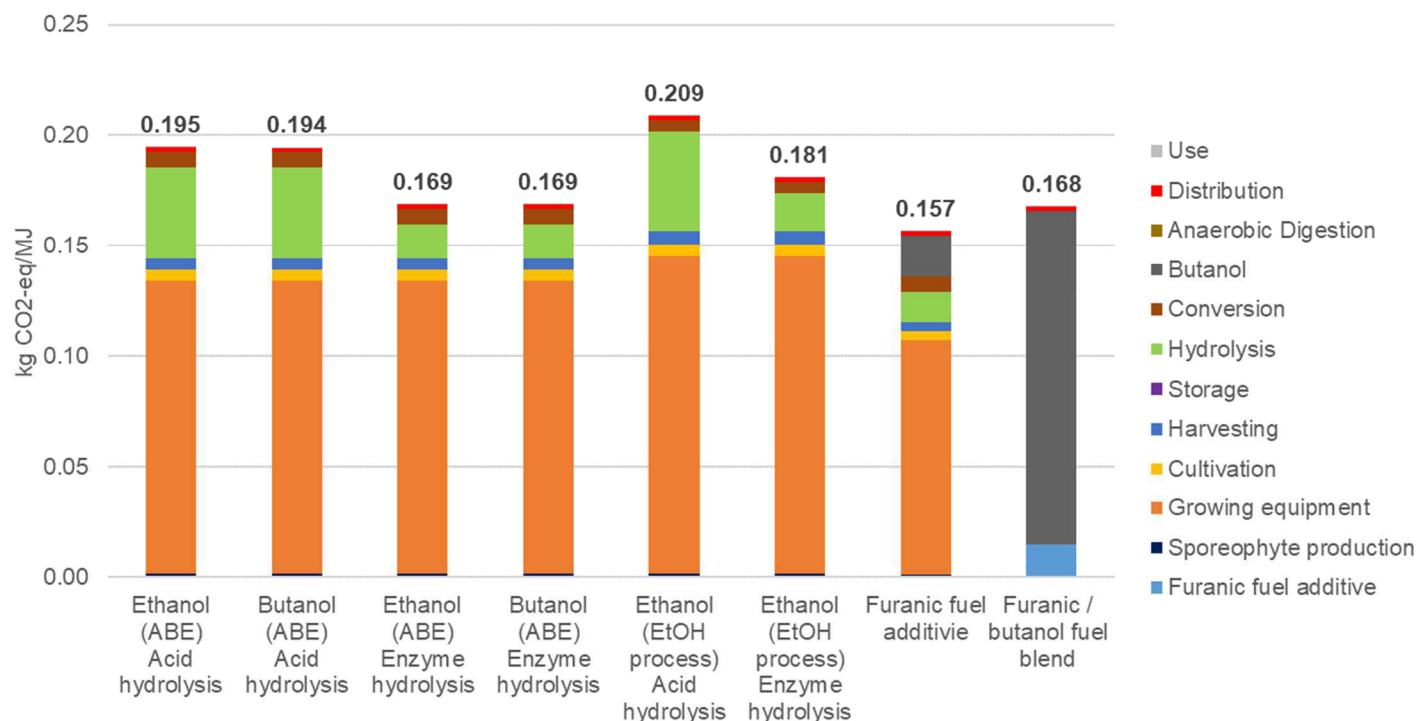
The results for all of the impact categories (see *Section 3.8*) are presented in *Table 5-1*.

Impact Category	Units	Ethanol (acid hydrolysis)	Ethanol (enzyme hydrolysis)	Ethanol from ABE (acid hydrolysis)	Ethanol from ABE (enzyme hydrolysis)	Butanol from ABE (acid hydrolysis)	Butanol from ABE (enzyme hydrolysis)	Furanics fuel additive	Furanic / butanol fuel blend
Climate change	kg CO ₂ eq	2.08E-01	1.81E-01	1.94E-01	1.69E-01	1.94E-01	1.68E-01	1.56E-01	1.69E-01
Ozone depletion	kg CFC-11 eq	4.33E-08	7.86E-09	4.04E-08	7.67E-09	4.03E-08	7.62E-09	1.74E-08	8.82E-09
Human toxicity, non-cancer effects	CTUh	3.91E-08	5.25E-08	3.81E-08	5.05E-08	3.81E-08	5.04E-08	2.44E-08	4.81E-08
Human toxicity, cancer effects	CTUh	5.80E-09	3.88E-09	5.53E-09	3.75E-09	5.53E-09	3.75E-09	3.46E-09	3.75E-09
Particulate matter	kg PM _{2.5} eq	7.34E-05	5.81E-05	7.07E-05	5.66E-05	7.06E-05	5.65E-05	5.02E-05	5.65E-05
Photochemical ozone formation	kg NMVOC eq	8.86E-04	8.11E-04	7.08E-04	6.39E-04	7.07E-04	6.38E-04	5.76E-04	6.40E-04
Acidification	molc H ⁺ eq	1.02E-03	8.84E-04	9.67E-04	8.41E-04	9.66E-04	8.40E-04	7.20E-04	8.37E-04
Terrestrial eutrophication	molc N eq	2.26E-03	2.27E-03	2.12E-03	2.13E-03	2.12E-03	2.12E-03	1.73E-03	2.11E-03
Freshwater eutrophication	kg P eq	4.74E-05	2.40E-05	4.59E-05	2.43E-05	4.59E-05	2.43E-05	2.20E-05	2.43E-05
Marine eutrophication	kg N eq	2.18E-04	2.55E-04	2.11E-04	2.45E-04	2.11E-04	2.45E-04	1.84E-04	2.41E-04
Freshwater ecotoxicity	CTUe	4.62E-01	5.21E-01	4.47E-01	5.01E-01	4.46E-01	5.00E-01	2.56E-01	4.79E-01
Water resource depletion	m ³ water eq	1.26E-03	8.81E-04	1.25E-03	9.02E-04	1.25E-03	9.01E-04	4.66E-04	8.62E-04
Mineral, fossil & renewable resource depletion	kg Sb eq	1.21E-05	8.17E-06	1.26E-05	8.98E-06	1.26E-05	8.98E-06	6.93E-06	8.83E-06

Table 5-1 impact results for the baseline scenarios of each fuel production route

5.1 Climate Change

Figure 5-1 Climate Change impact results for the baseline scenarios of each fuel production route (total value shown above each column)



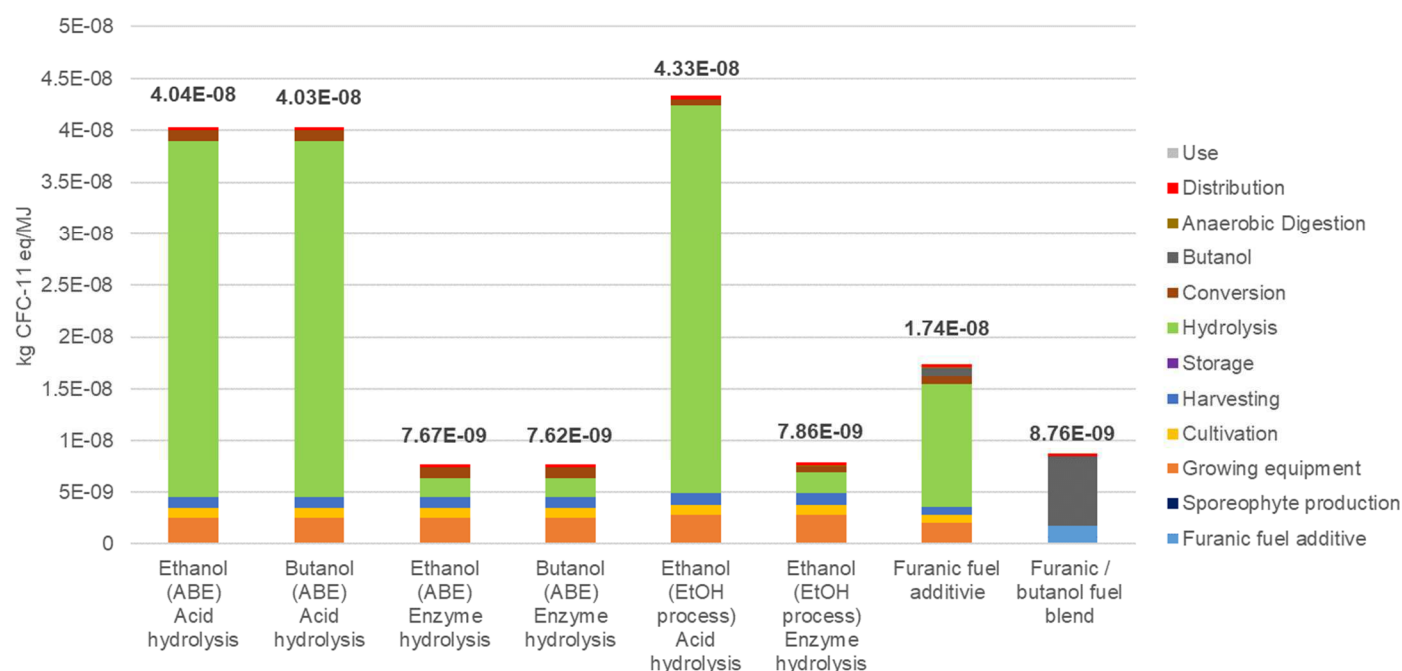
As can be seen in Figure 5-1, the biggest contributor to climate change impact, across all scenarios, is the growing equipment used in seaweed production (68-79%) for all scenarios. The 10mm chain contributes most to the growing equipment (50%).

Figure 5-1 shows that the furanic fuel additive scenario results in the lowest climate change impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis.

Fossil carbon dioxide emissions to air are the highest contributor to this impact category (90-96%), the majority arising from the manufacture of growing equipment.

5.2 Ozone Depletion

Figure 5-2 Ozone depletion impact results for the baseline scenarios of each fuel production route (total value shown above each column)



As can be seen in *Figure 5-2*, scenarios employing enzyme hydrolysis perform the best for this impact category. If acid hydrolysis is used, the hydrolysis stage is the dominant contributor (86%), and the principal impact drivers are the production of hydrochloric acid (31% of fuel production) and sodium hydroxide (56% of fuel production). If enzyme hydrolysis is used, the largest impact contribution is from the growing equipment (33%-35%). The 10mm chain contributes most from the growing equipment (40%). For the furanic fuel additive, the biggest impact contribution is in the hydrolysis stage (68%), caused by the production of sodium hydroxide that is used for neutralization.

When acid hydrolysis is used (ethanol, ABE and furanics), the largest contributor to this impact category is tetrachloro-methane emissions to air as a result of the production of hydrochloric acid and sodium hydroxide (63%-74%). For enzyme hydrolysis, the largest contributor to this impact category is the emission of bromotrifluoro-methane emissions to air, primarily as a result of the production of diesel used in cultivation, harvesting and the transport of the growing equipment (46%-47%).

5.3 Human Toxicity, Non-Cancer

Figure 5-3 Human toxicity, non-cancer impact results for the baseline scenarios of each fuel production route (total value shown above each column)

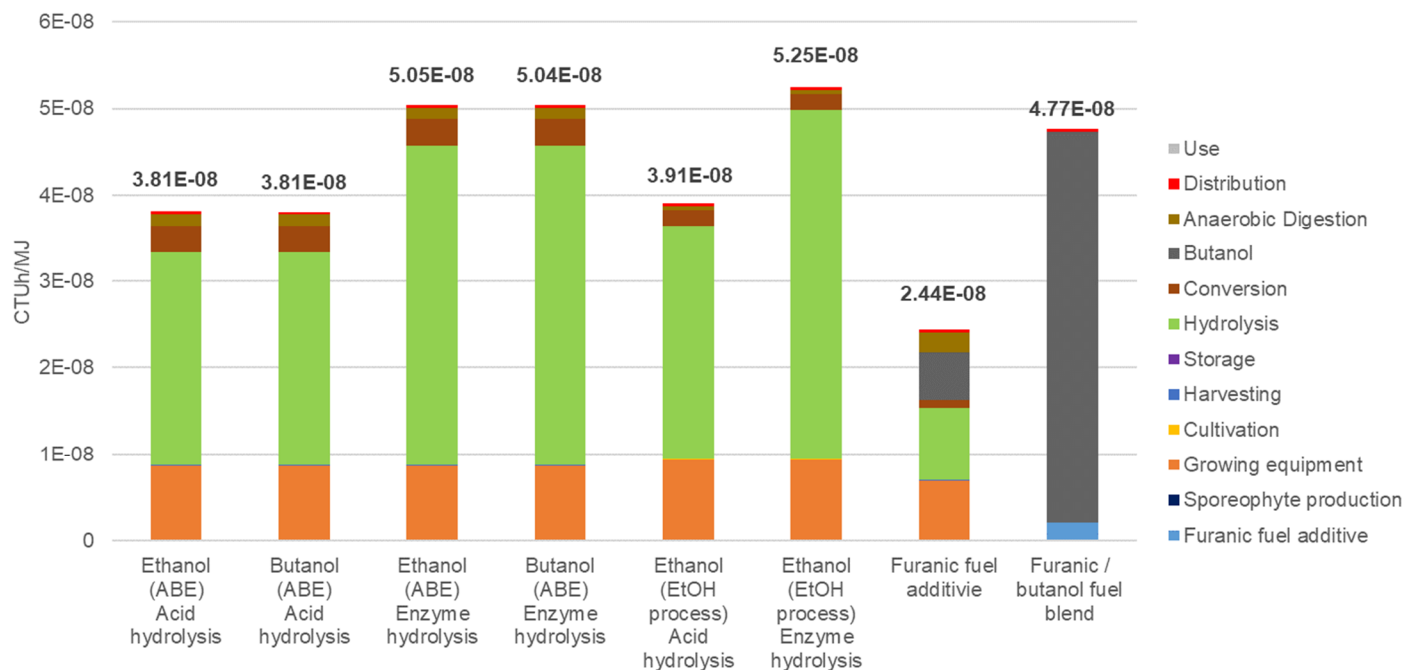


Figure 5-3 shows that, for the ABE and ethanol scenarios, the human toxicity (non-cancer) impact contribution is dominated by the hydrolysis stage. This contribution results from the production of hydrochloric acid and sodium hydroxide for acid hydrolysis, and the enzymes for enzyme hydrolysis (73-77%). For the furanic fuel, the sodium hydroxide used for neutralization is the primary contributor. The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by acid hydrolysis have a lower impact than if produced by enzyme hydrolysis.

For the acid hydrolysis and furanic blend scenarios, mercury emissions to air are the largest contributor to this impact category (44%), the majority arising from the manufacture of growing equipment. For the enzyme hydrolysis and furanic/butanol blend scenarios, zinc emissions to land are the largest contributor to this impact category (68%), the majority arising from the production of enzymes.

5.4 Human Toxicity, Cancer

Figure 5-4 Human toxicity, cancer impact results for the baseline scenarios of each fuel production route (total value shown above each column)

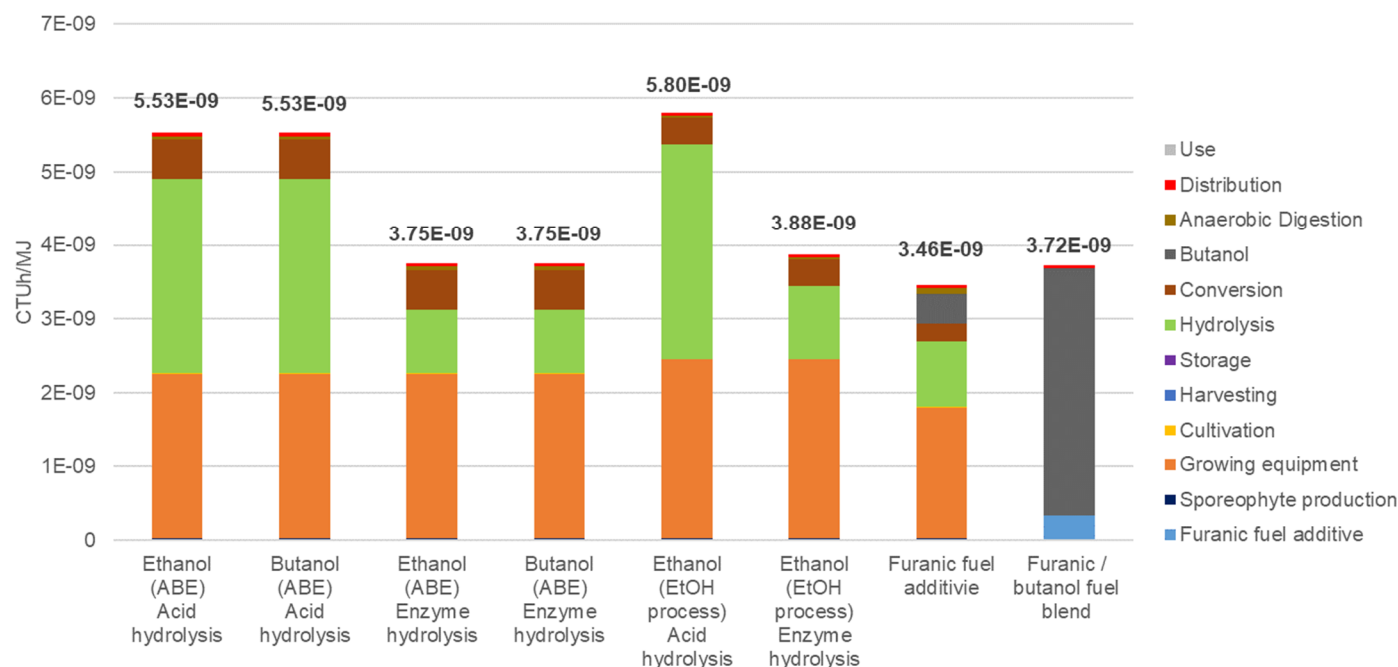


Figure 5-4 shows that, for the ethanol and ABE scenarios, the human toxicity (cancer) impact varies depending on the method of hydrolysis. If acid hydrolysis is used, the largest impact contribution comes from the hydrolysis (48-50%) step. If enzyme hydrolysis is used, the growing equipment dominates (60-63%). The PE pipe contributes most to the growing equipment (47%). For the furanic fuel additive, the largest impact comes the growing equipment (51%). The furanic fuel additive scenario results in the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis.

Chromium VI emissions to water make the highest contribution to this impact category (48%-65%), the majority arising from the production of the growing equipment where enzyme hydrolysis is used or production of hydrochloric acid and sodium hydroxide for scenarios using acid hydrolysis.

5.5 Particulate Matter

Figure 5-5 Particulate matter impact results for the baseline scenarios of each fuel production route (total value shown above each column)

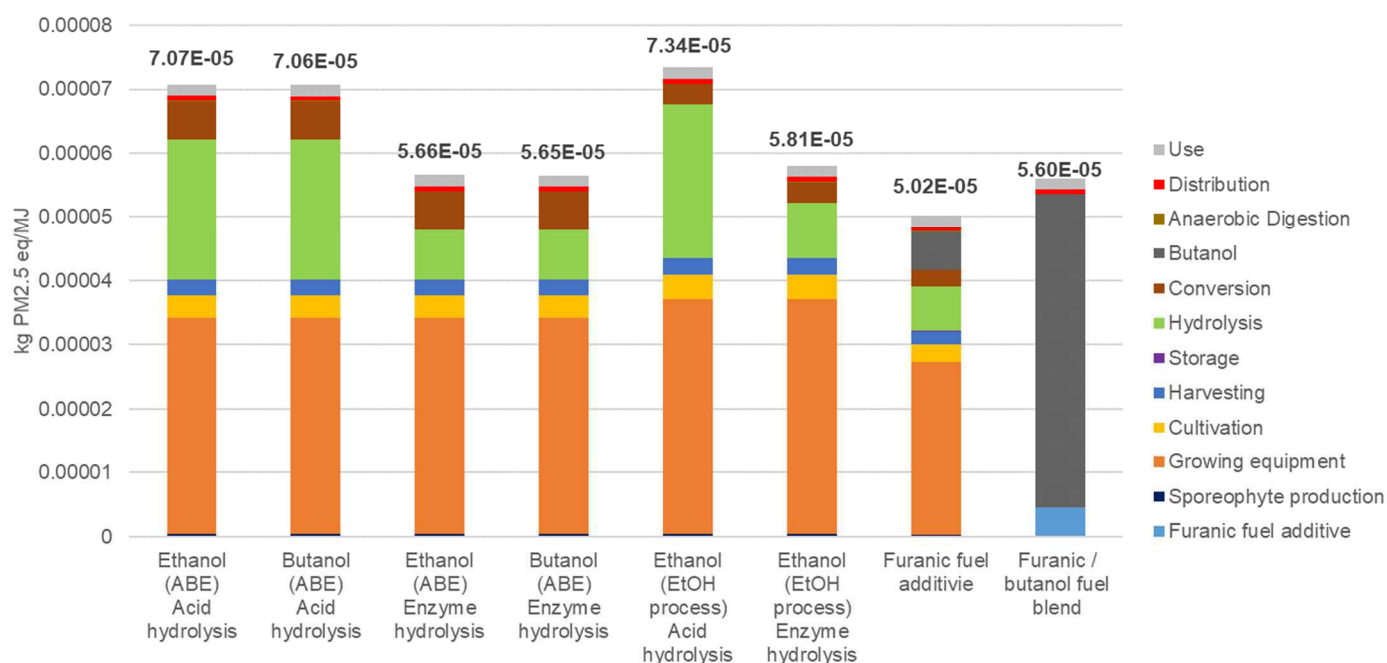


Figure 5-5 shows the particulate matter contributions for each scenario. For all scenarios, approximately half of the impact is associated with the seaweed growing equipment (48-63%). For the scenarios with acid hydrolysis, the hydrolysis causes the next biggest contribution (approximately 30%). The 10mm chain contributes most to the growing equipment (45%).

PM_{2.5} emissions to air make the highest contribution to this impact category (44%), the majority arising from the manufacture of growing equipment (45%).

Figure 5-5 shows that the furanic fuel additive scenario results in the lowest climate change impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis.

5.6 Photochemical Ozone Formation

Figure 5-6 Photochemical ozone formation impact results for the baseline scenarios of each fuel production route (total value shown above each column)

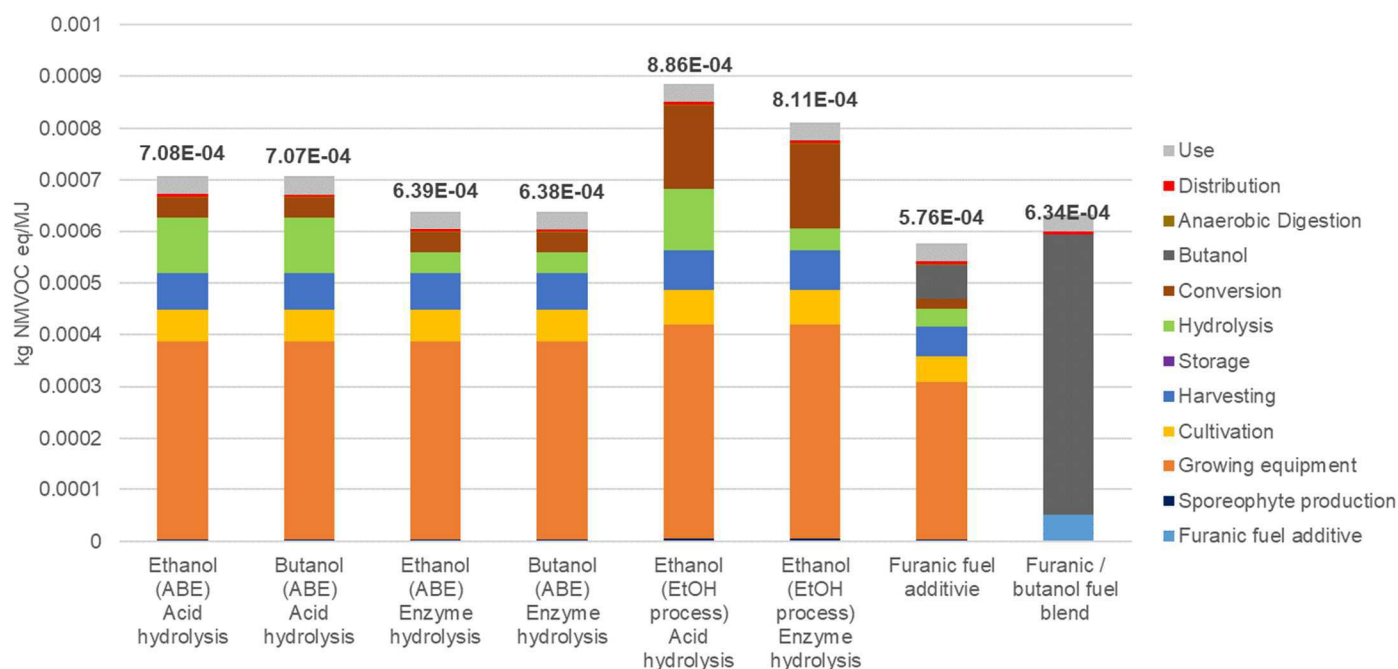


Figure 5-6 shows the photochemical ozone formation impacts. For all scenarios, the main contribution is from the seaweed growing equipment (47-60%). The 10mm chain contributes most to the growing equipment (39%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by acid hydrolysis have a lower impact than if produced by enzyme hydrolysis.

Nitrogen oxide emissions to air make the highest contribution to this impact category (30%-40%), the majority arising from the marine diesel use in seaweed cultivation / harvesting and growing equipment production. Nitrogen dioxide emissions arising from the production of the growing equipment also make a significant contribution to the photochemical ozone formation impact (20%-25%).

5.7 Acidification

Figure 5-7 Acidification impact results for the baseline scenarios of each fuel production route (total value shown above each column)

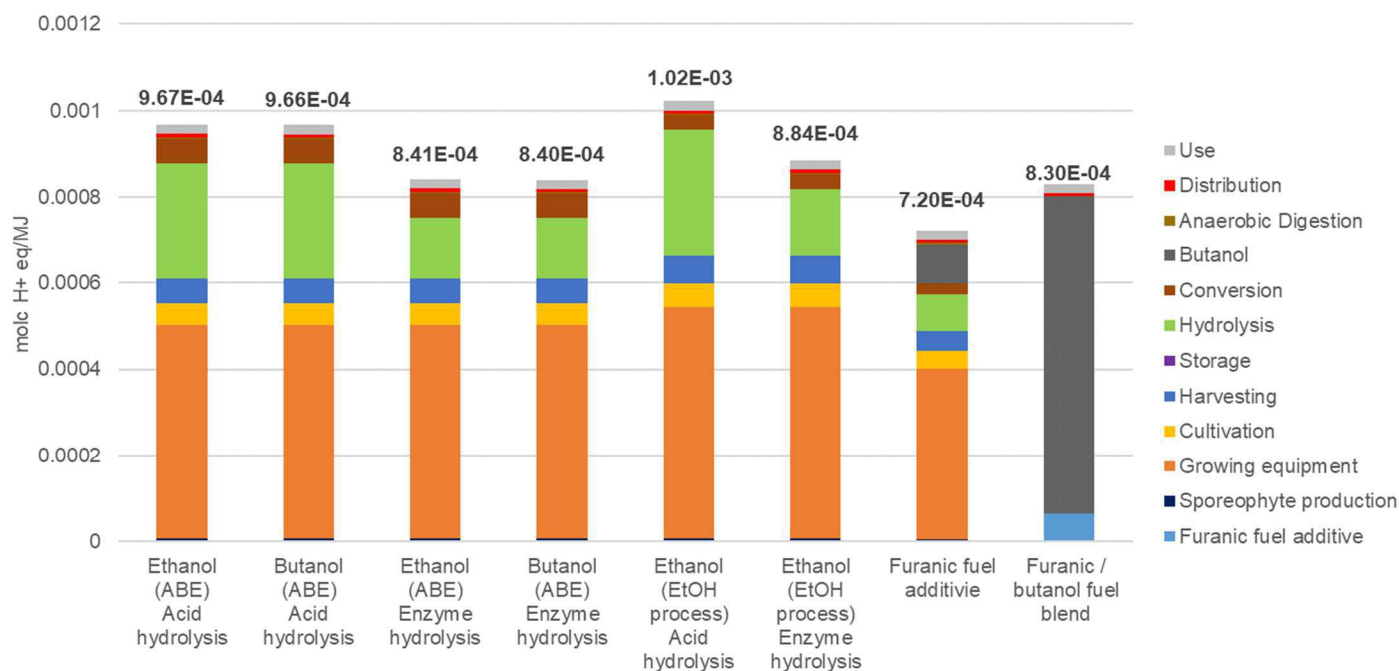
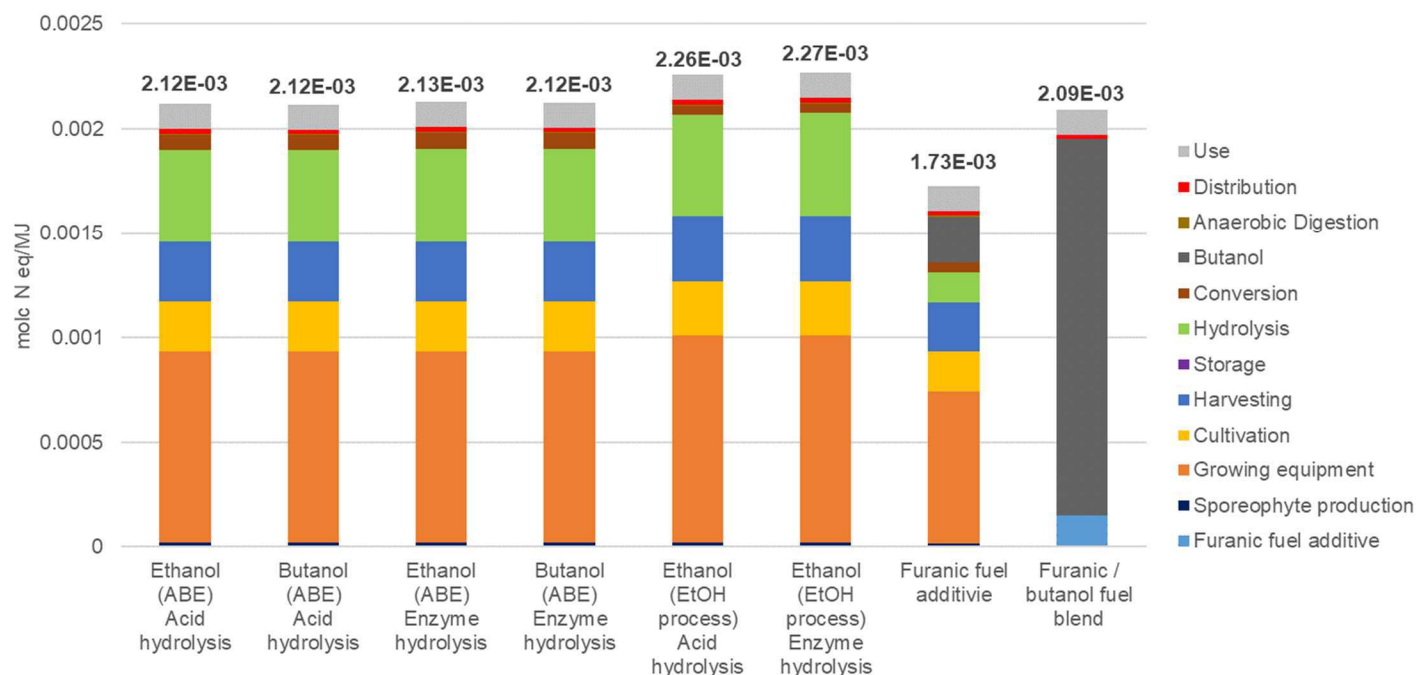


Figure 5-7 shows the acidification impact contributions for each scenario. For all scenarios, the largest contribution is from the manufacture of the seaweed growing equipment (50-60%). The 10mm chain contributes most to the growing equipment (46%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis.

Sulphur dioxide emissions to air make the highest contribution to this impact category (55-63%), the majority arising from the manufacture of growing equipment.

5.8 Terrestrial Eutrophication

Figure 5-8 Terrestrial eutrophication impact results for the baseline scenarios of each fuel production route (total value shown above each column)



Terrestrial eutrophication impact contributions for each scenario can be seen in Figure 5-8. For all scenarios, the biggest impacts are from seaweed growing equipment (40-45%). The 10mm chain contributes most to the impact associated with growing equipment (45%).

Nitrogen oxide emissions to air make the highest contribution to this impact category (50-63%), the majority arising from the seaweed production (production of growing equipment and marine diesel use in seeding / harvesting).

The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Ethanol produced through the EtOH process has a greater impact than either ethanol or butanol produced by the ABE process, regardless of the method of hydrolysis.

5.9 Freshwater Eutrophication

Figure 5-9 Freshwater eutrophication impact results for the baseline scenarios of each fuel production route (total value shown above each column)

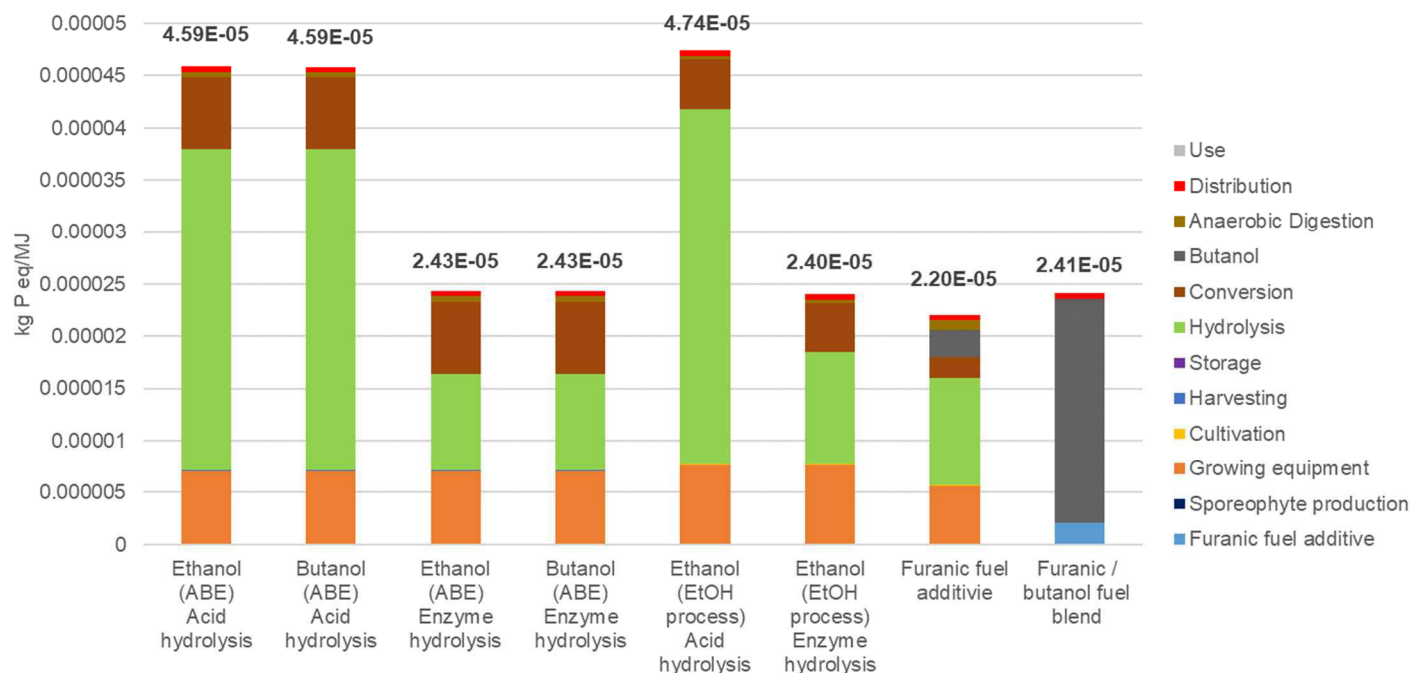
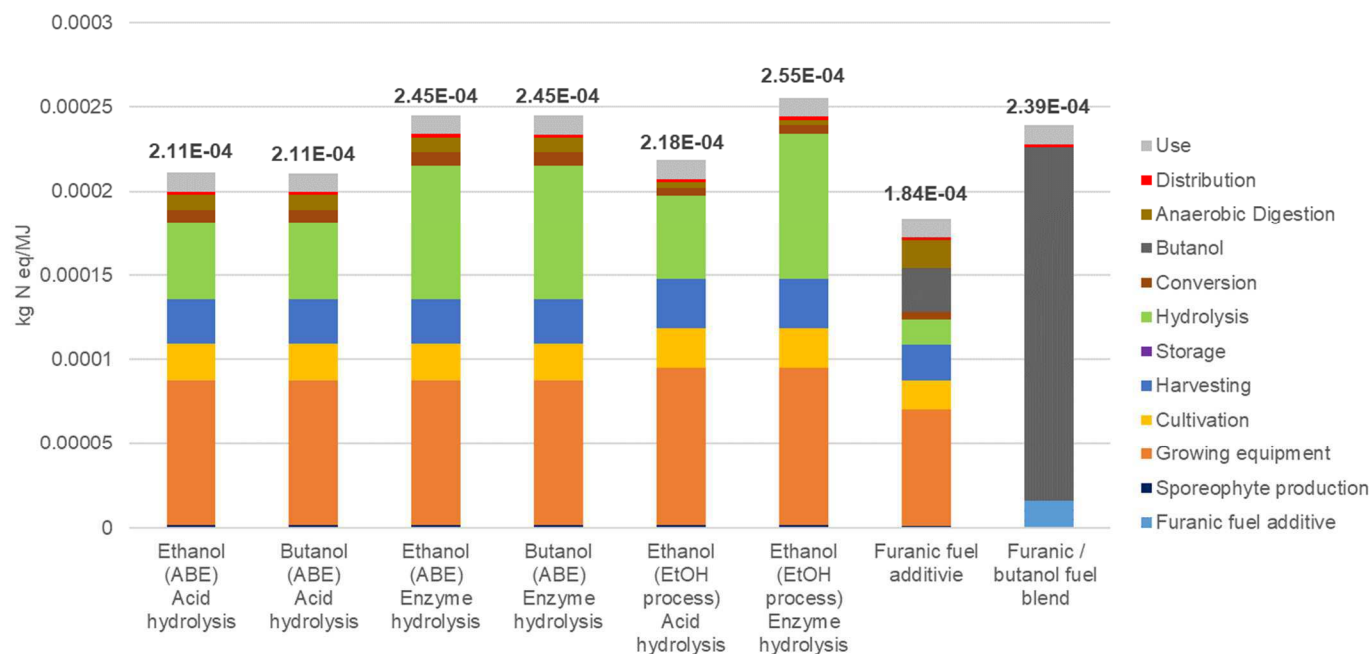


Figure 5-9 shows the freshwater eutrophication impact contributions for each scenario. In the acid hydrolysis ethanol and ABE scenarios, the biggest contribution is from the hydrolysis stage (67-71%), caused by sodium hydroxide (44% of fuel production) and hydrochloric acid production (25% of fuel production). For ethanol and ABE with enzyme hydrolysis, the largest contribution is from the hydrolysis stage, driven by enzyme production (38-44%). For furanic fuel, the impacts are driven from the hydrolysis stage in fuel production (45%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis.

Phosphate emissions to water make the highest contribution to this impact category (98%), the majority arising from the manufacture of growing equipment or from the enzymes if enzyme hydrolysis was used.

5.10 Marine Eutrophication

Figure 5-10 Marine eutrophication impact results for the baseline scenarios of each fuel production route (total value shown above each column)



Marine eutrophication impact contributions for each scenario are shown in *Figure 5-10*. In the acid hydrolysis ethanol and ABE scenarios, the greatest contribution is from the seaweed growing equipment (41-43%). For ethanol and ABE with enzyme hydrolysis, the largest contributions are from the hydrolysis stage (32%), driven by enzyme production, and from the growing equipment (35-37%). For the furanic fuel additive, the largest impact contribution is from the seaweed growing equipment (38%). The 10mm chain contributes most to the growing equipment (45%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by acid hydrolysis have a lower impact than if produced by enzyme hydrolysis.

Nitrogen oxide emissions to air make the highest contribution to this impact category (40-55%), the majority arising from the seaweed harvesting.

5.11 Freshwater Ecotoxicity

Figure 5-11 Freshwater ecotoxicity impact results for the baseline scenarios of each fuel production route (total value shown above each column)

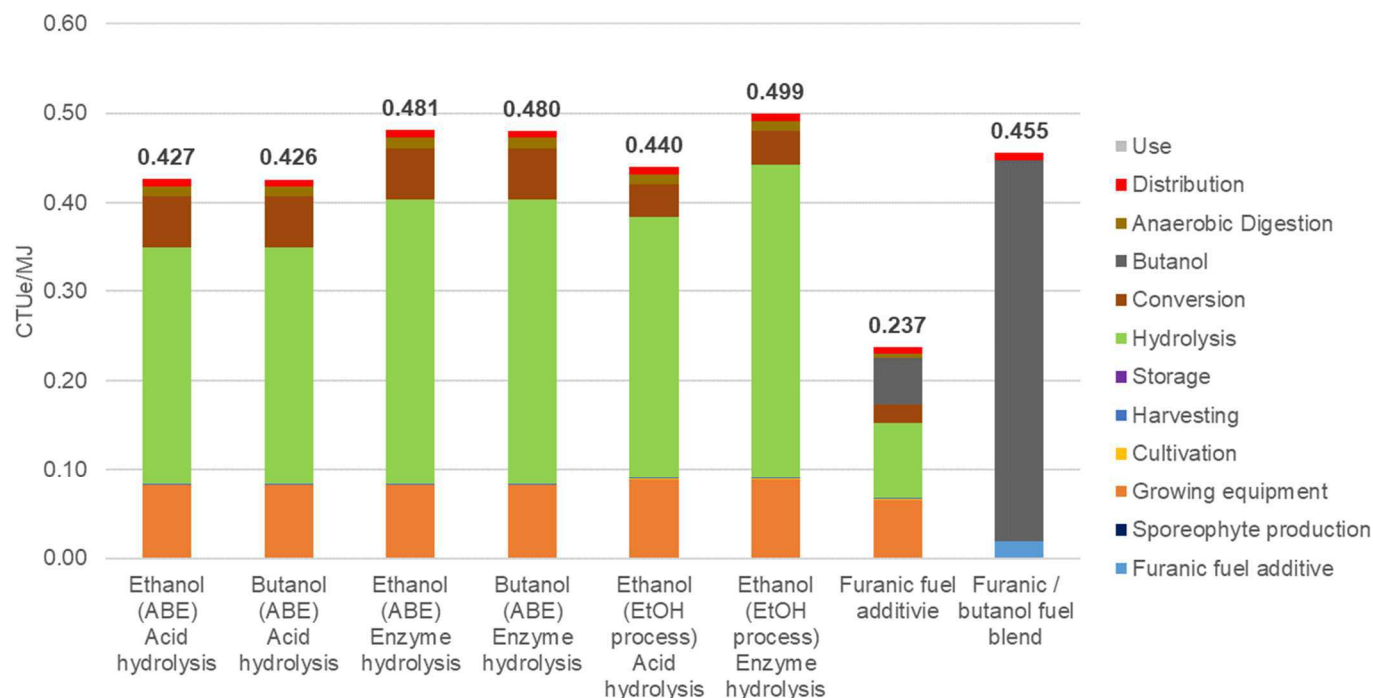


Figure 5-11 shows the freshwater ecotoxicity impact contributions for each scenario. For all ethanol and ABE scenarios, the largest impacts are from the hydrolysis process in fuel production (62-70%). For furanic fuel, the largest impacts come from hydrolysis (36%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by acid hydrolysis have a lower impact than if produced by enzyme hydrolysis.

For acid hydrolysis scenarios, zinc emissions to water make the largest contribution to this impact category (55%), the majority arising from the manufacture of growing equipment. For enzyme hydrolysis scenarios, chlorothalonil emissions to land are the largest contributor to this impact category (49%-51%), the majority arising from the production of the enzymes.

5.12 Water Resource Depletion

Figure 5-12 Water resource depletion impact results for the baseline scenarios of each fuel production route (total value shown above each column)

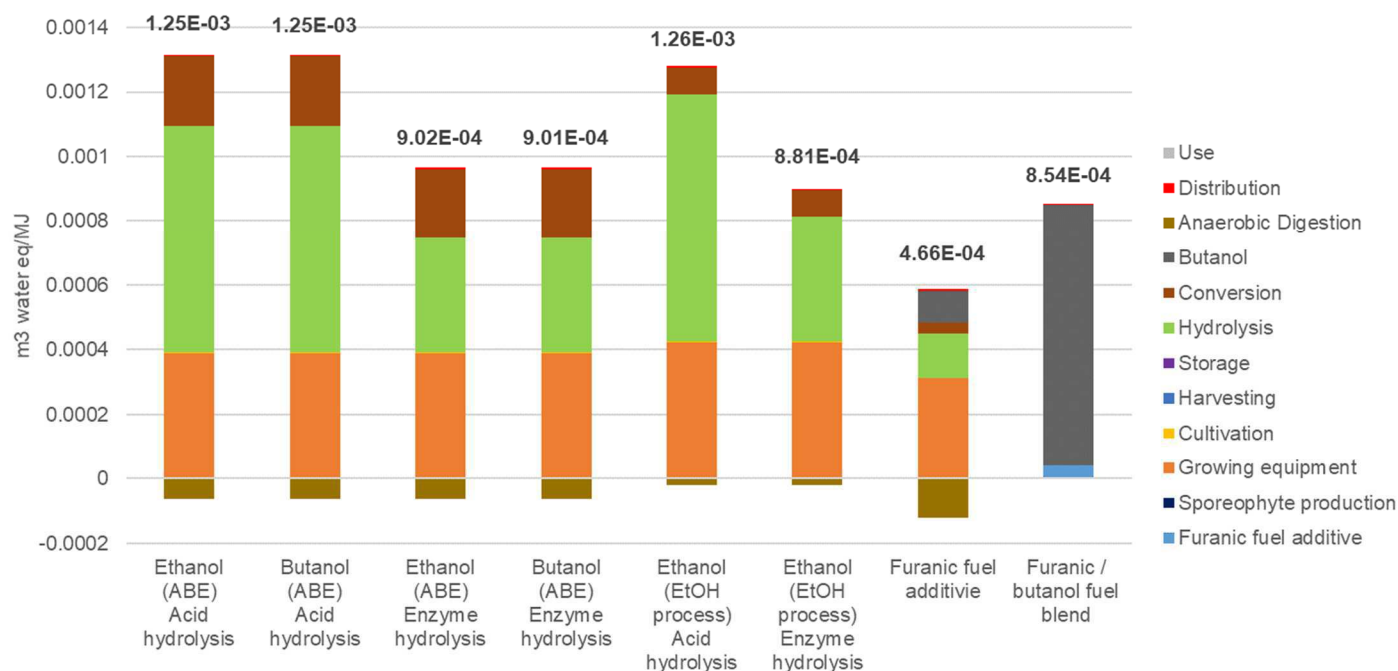


Figure 5-12 shows the water resource depletion impact associated with each scenario. For ethanol and ABE scenarios with acid hydrolysis, the hydrolysis processes causes the largest water resource depletion impact (56-61%). For the ethanol and ABE scenarios that use enzyme hydrolysis, the two biggest impacts are from the seaweed growing equipment (43-48%) and the hydrolysis stage (39-44%). For the furanics fuel scenario, the seaweed growing equipment is the largest contributor (67%). The 10mm chain contributes most to the growing equipment (52%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis.

The negative values shown for all the biofuel products represent the discharge of water to the environment from the biofuel production process.

Water use for energy generation (turbine water) makes the highest contribution to this impact category, the majority arising as a result of the manufacture of growing equipment or the production of enzyme in the case of enzyme hydrolysis.

5.13 Mineral, Fossil & Renewable Resource Depletion

Figure 5-13 Water resource depletion impact results for the baseline scenarios of each fuel production route (total value shown above each column)

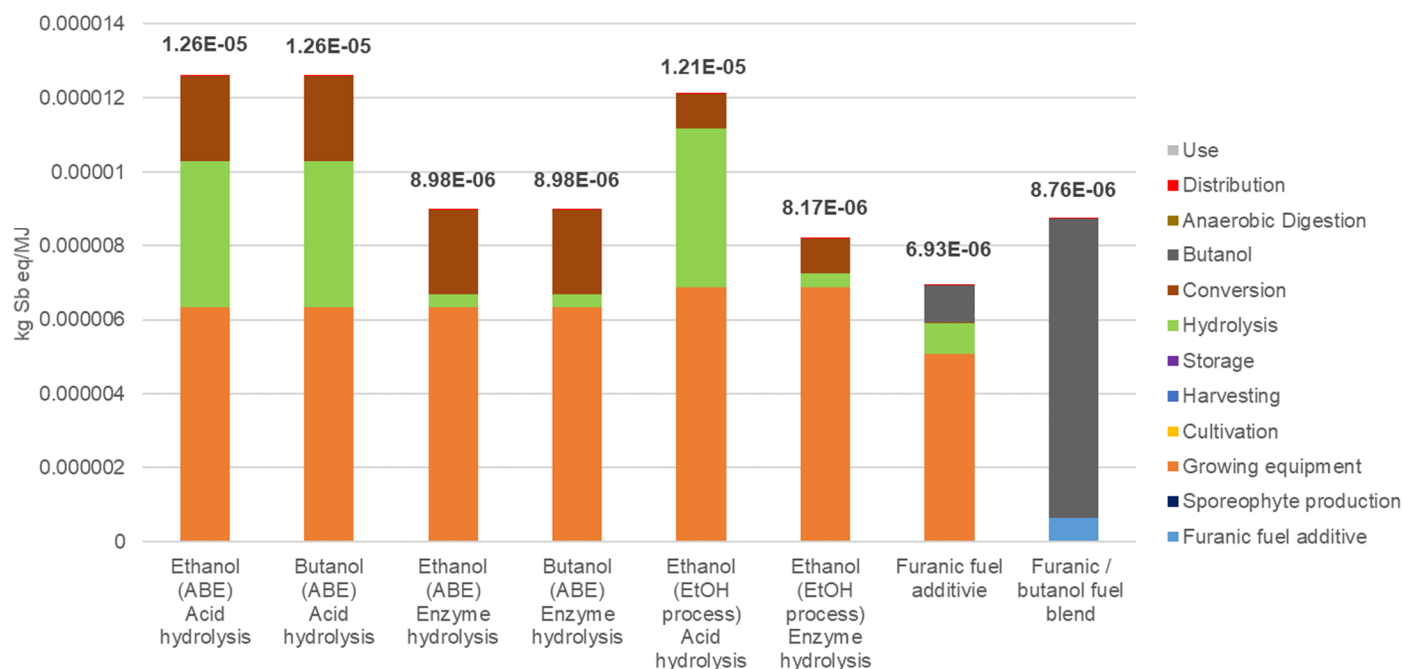


Figure 5-13 shows the resource depletion impacts for all scenarios. In all scenarios, the largest impact contribution is made by the seaweed growing equipment (50-56% acid hydrolysis and 70-83% enzyme hydrolysis). The 10mm chain contributes most to the growing equipment (82%). The furanic fuel additive scenario has the lowest impact per MJ. However, once blended with bio-butanol to produce a furanic/butanol (1:9) fuel blend, the impact per MJ is equivalent to the ethanol (ABE) and butanol (ABE) enzyme hydrolysis scenarios. Butanol and ethanol produced by enzyme hydrolysis have a lower impact than if produced by acid hydrolysis

The use of lead makes the highest contribution to this impact category (38-44%), the majority arising from manufacture of growing equipment.

6 INTERPRETATION

In this section, the main findings of the assessment are appraised, tested through sensitivity analysis and evaluated in the context of Renewable Energy Directive, as follows:

- A summary of findings and key contributions to ‘cradle-to-grave’ impacts for the MacroFuel biofuels;
- A data quality assessment ;
- Sensitivity analysis to investigate key contributions to the assessment;
- Benchmark the biofuels assessed under the MacroFuels project against:
 - Sustainability criteria for GHG emissions under Renewable Energy Directive (2018/2001); and
 - Equivalent conventional, fossil-based, fuels and currently available biofuels.

6.1 Summary of Key Findings

Table 6-1 summarises the main contributions to each impact.

The main contributors to all of the environmental impact categories assessed were either the seaweed growing 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 not insignificant, 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 approximately 14% of the total impact, respectively.

Table 6-1 a summary of the lifecycle stage with the largest contributions to each impact categories for all biofuel scenarios.

Impact Category	ABE Process & EtOH Process	Furanic Fuel ¹
Climate change	Growing equipment (68-79% of total)	Growing equipment (76% of total)
Ozone depletion	<i>Acid hydrolysis</i> : hydrolysis stage (86% of total) <i>Enzyme hydrolysis</i> : Growing equipment (33%-35%) <i>Enzyme hydrolysis</i> : Growing equipment (33-35%)	Hydrolysis stage (68% of total).
Human toxicity, non-cancer effects	Hydrolysis process (65%-77%)	Hydrolysis process (34%)
Human toxicity, cancer effects	<i>Acid hydrolysis</i> : hydrolysis stage (48%-50%) <i>Enzyme hydrolysis</i> : growing equipment (60%-63%)	Growing equipment (51% of total)
Particulate matter	Growing equipment (48-63% of total)	Growing equipment (54% of total)
Photochemical ozone formation	Growing equipment (47-60% of total)	Growing equipment (53% of total)
Acidification	Growing equipment (51-60% of total)	Growing equipment (55% of total)
Terrestrial eutrophication	Growing equipment (42-44% of total)	Growing equipment (42% of total)
Freshwater eutrophication	Hydrolysis process (38% - 72%)	Hydrolysis process (47%)
Marine eutrophication	Growing equipment (35%-43% of total)	Growing equipment (38% of total)
Freshwater ecotoxicity	Hydrolysis process (62%-70% of total)	Hydrolysis process (36% of total)
Water resource depletion	<i>Acid hydrolysis</i> : hydrolysis stage (56-61% of total) <i>Enzyme hydrolysis</i> : growing equipment (43-48%)	Growing equipment (67%)
Mineral, fossil & renewable resource depletion	Growing equipment (50%-84% of total)	Growing equipment (73% of total)

¹ Only results for the furanic fuel additive (without blended butanol) are shown here. For the furanic / butanol blend, the largest impact is from the butanol production for all of the impact categories.

Within the growing equipment life cycle stage, the chain used to secure the sheetnets to the anchors and buoys and keep them underwater accounts for 40% or more of the impact from the growing equipment for all environmental impact categories except for human toxicity (cancer effects), freshwater eutrophication and freshwater ecotoxicity. For these impact categories, the impact from producing buoys and HDPE pipe accounts for more than 75% of the impact from the growing equipment.

For ethanol (either EtOH process or ABE process) and butanol products, production via acid hydrolysis results in higher impacts than enzyme hydrolysis for all of the impact categories assessed, except for freshwater ecotoxicity, marine eutrophication, terrestrial eutrophication and human toxicity (non-cancer).

The impact of the production of ethanol and butanol via the ABE process is lower than that of ethanol produced by the EtOH process, for all of the impact categories, except for freshwater eutrophication, water resource depletion and mineral, fossil and renewable resource depletion.

The impact of the production of the furanic fuel additive is lower than that of ethanol or butanol produced either by the ABE or the EtOH processes for all of the impact categories other than ozone depletion. However, once blended with bio-butanol, the impact per MJ approaches that of the butanol produced via ABE process (enzyme hydrolysis), as this is the butanol with which it is assumed to be blended.

6.2 Data Quality Assessment

Taken together, the data used in this study are considered by the authors to be a good representation of the proposed system. However, there is a high reliance on secondary data, as this is a study of a concept and the anticipated performance of the current design. The data quality is considered sufficient for meeting the goal of the study.

The data quality for this study is summarised in Table 6-2 below.

Table 6-2 Data Quality Assessment

Parameter	Data Quality Assessment
Time-related coverage	The data relates to current design in 2019. Secondary data relate to 2000 – 2017 and represent current performance.
Geographical coverage	The data represent production of seaweed and biofuels in Northern Europe.
Technology coverage	Data used to assess the MacroFuel concept are representative of current technology for seaweed cultivation and bio-refinery design.
Precision	There is variability within the data used to assess the MacroFuels concept. Sensitivity analysis has been undertaken to determine the significance of this variability.
Completeness	All anticipated emissions from all life cycle stages within the system boundary are included. Full life cycle inventories from the ILCD have been used to assess the environmental impacts.
Representativeness	The data used in the study represent current performance in Northern Europe.
Consistency	To ensure consistency, checks were made on mass and energy data from each source and clarification and additional inputs were sought where required.
Reproducibility	Full information about the impact methods used (ILCD) and the data values (see <i>Annex B</i>) have been provided to allow independent practitioners to reproduce the study.
Sources of the data	Data were derived from credible sources (Ecoinvent 3.4, ELCD, GREET, RED, Biograce) and were selected to represent European production or global where appropriate.

6.3 Sensitivity Analysis

Sensitivity analysis allows variables that have been found to influence the results to the greatest extent and alternative assumptions / data to be assessed. The sensitivity of the results to key modelling assumptions, model inputs, seaweed storage approaches and alternative growing materials are

considered. Sensitivity results for all impact categories assessed are presented in *Annex C*. As climate change impact is the key driving rationale for the development of the MacroFuel biofuels, and other impact category sensitivities align, only the sensitivity analysis results for the climate change impact are presented in this chapter.

The baseline scenarios for the sensitivity analysis are the EtOH and ABE enzyme hydrolysis routes for the production of ethanol, butanol and furanic fuel additive.

The sensitivity analysis cover the following:

- Allocation to co-products;
- Variation of model inputs;
- Carbon sequestration from seaweed; and
- Alternative production scenarios.

6.3.1 Allocation to Co-Products

For this study, impacts have been allocated to co-products based on energy content, as required by RED. An alternative would be to allocate the impacts based on the economic value of co-products and to use system expansion for non- fuel products. The use of system expansion for the fuel co-products is not appropriate in the context of this study, as a goal of the study is to benchmark fuel products against conventional or other bio sources.

Figure 6-1 shows the consequence on the climate change impact for the baseline MacroFuel products (i.e. enzyme hydrolysis used for EtOH and ABE processes) when:

- Economic allocation is used instead of allocation by energy content for all fuel co-products (i.e. ethanol, butanol, acetone and biogas); or
- System expansion is used to accommodate the use of digestate, produced from anaerobic digestion, as a fertilizer.

6.3.1.1 Economic Allocation vs Allocation by Energy Content

Figure 6-1 shows that the climate change impact is increased for all the MacroFuel biofuels when economic allocation is used, from a 35% increase for ethanol produced by the EtOH process to approximately a 10% increase for ethanol / butanol produced by the ABE process. There are no fuel co-products from the furanic fuel additive or furanic blend production, as all biogas produced is required in the process, and so any increase change in impact is related to changes in the impact the increase in the climate change impact from the production of butanol.

The results suggest that the choice of allocation method can make a significant difference to the climate change impact results. The use of economic allocation results in increased impact per MJ for the MacroFuel biofuel products. The increases are due primarily to the exported biogas being a key

co-product from the production of these biofuels. Current economic values for natural gas and biogas are significantly lower than for ethanol, butanol and acetone on a per MJ basis when compared to the lower heating value of the co-products, which is used to establish the energy allocation (see **Fejl!** **Henvisningskilde ikke fundet.** Table 6-3 below). This means that less of the climate change impact from the EtOH and ABE processes is allocated to the biogas and more is allocated to the ethanol and butanol, which have higher economic values per MJ.

Table 6-3 Economic values and energy content of Macrofuels products / co-products

Product / Co-product	Economic Value (EUR/tonne _{dw})	Lower Heating Value (MJ/kg)	Economic Value (EUR/MJ)	Source /comment
Ethanol	468	27	17.3	2015-2017 average price (Finanzen, 2018)
Butanol	579	33	17.5	Based on Ethanol price corrected for heating value
Acetone	700	29.6	23.6	2015-2016 average price, valued as a chemical (ICIS, 2018)
Biogas (methane content only)	475	50	9.5	Projected natural gas price in 2020 (Schoots, 2015)

6.3.1.2 Digestate Benefit Through System Expansion

The RED method considers digestate produced from anaerobic digestion to be a residue to which no production impact is attributed, either through allocation by energy content or via system expansion. However, RED does allow for the use of system expansion in the context of studies to support policy. This sensitivity analysis assesses the potential effect on the climate change impact of using system expansion and displacing the production of inorganic fertilisers.

The digestate produced from the anaerobic digestion process has the potential to be used as a fertiliser. The nitrogen (N), phosphorous (P) and potassium (K) content of the digestate produced by each of the three processes was established based on the modelled composition of the digestate, as shown in Table 6-4 below

Table 6-4 Digestate characteristics (digestate wet weight)

Process	Digestate (kg / tonne seaweed ww)	N Content (%)	P Content (%)	K Content (%)
EtOH process	190	0.51%	0.10%	0.17%
ABE process	432	0.32%	0.09%	0.09%
Furanics process	436	0.55%	0.00%	0.59%

The digestate is assumed to displace the production of inorganic fertilisers on a 1:1 basis by weight of nutrient applied. Impacts from application of the nutrients to agricultural land are assumed to be equal for the digestate and the inorganic fertiliser. The secondary data sources for displacement of the production of inorganic fertilisers are shown in *Annex B*.

Figure 6-1 Sensitivity analysis for allocation assumptions

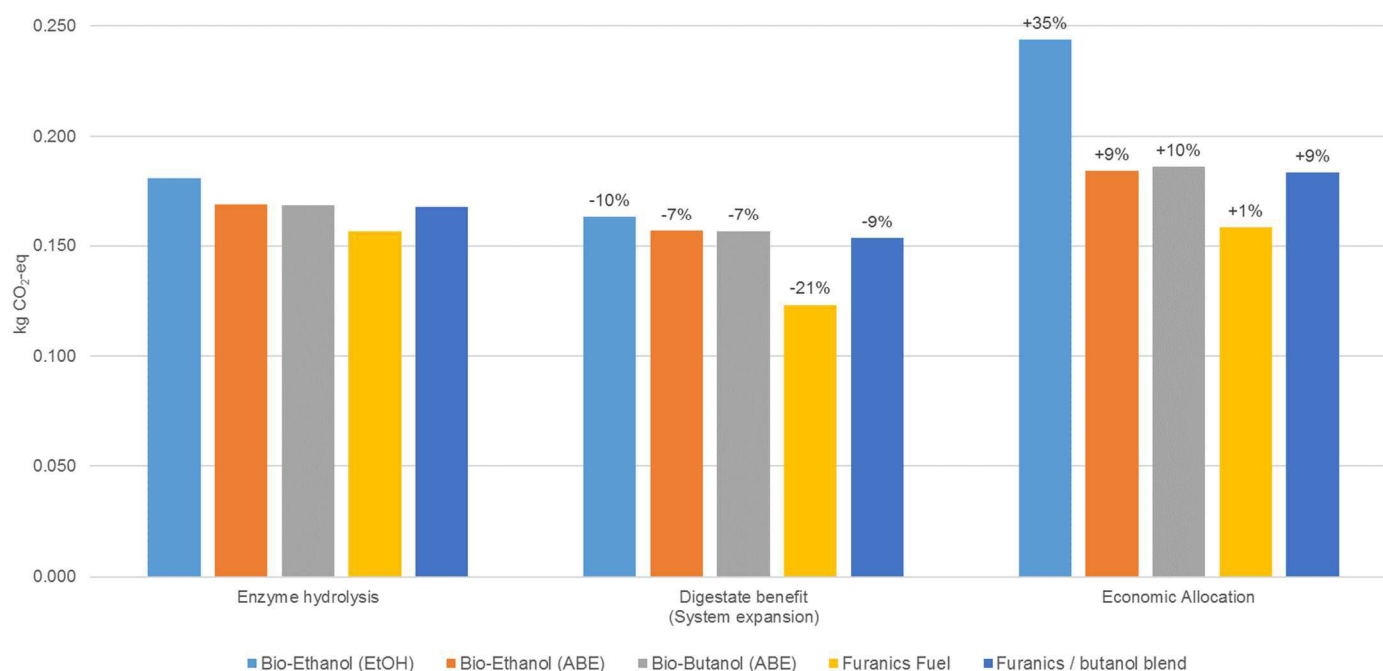


Figure 6-1 shows that including a beneficial use for the digestate through system expansion decreases the ‘cradle to grave’ climate change impact from the baseline by 7%- 9% for all MacroFuel biofuels, except the unblended furanic fuel additive, which is reduced by 23%. The majority of the reduction (>90%) is a result of the displacement of nitrogen fertiliser production. The larger reduction

seen for the furanics fuel is a result of the greater amount of digestate produced than for the EtOH process and the increased nitrogen content of the digestate compared to the digestate from the ABE process. However, as the furanics process involves the use of toluene in the biphasic reaction and there may be the potential for this to enter the anaerobic digester, further testing would be needed to confirm that the toluene was degraded sufficiently for the digestate product to be safely applied to agricultural land.

6.3.2 Variation of Key Models Inputs

To investigate the impact of further technology development, as well as uncertainty in the assumptions, a number of sensitivity analyses have been undertaken to determine effects on the climate change impact. For each scenario, parameters have been selected for evaluation, based on the level of uncertainty associated with them and/or the level of their contribution to the overall results. With the exception of seaweed yield, an arbitrary increase/ decrease of 50% for each parameter has been used. Seaweed yield is limited to a 20% change. The sensitivity analyses focus on seaweed production and the hydrolysis stage of biofuels processing, as together these represent more than 90% of the total baseline impact. Details for each sensitivity analysis scenario are shown in Table 6-5 below.

Table 6-5 details of each sensitivity scenario assessed along with the code used.

Scenario		Description
Baseline	Enzyme Hydrolysis	Products produced using the EtOH or ABE processes are produced using enzyme hydrolysis.
Seaweed yield	+20%	Change in seaweed yield assessed are limited to +/- 20%.
	-20%	
Seeding / harvesting fuel use	+50%	Represents change in amount of marine diesel used in the automated machines/platforms for seeding and harvesting stages during seaweed cultivation. These machinery have not been fully developed yet and so fuel use has been estimated as 10 l/h operation based on agricultural / forestry equipment of a similar size.
	-50%	
Growing equipment lifetime	+50%	Represents change in assumed useful lifetimes for all components used for growing equipment. The lifetime for the growing equipment are a key assumption given the large impact contribution.
	-50%	
Enzyme use	+50%	Represents a change in the impact from enzyme use in hydrolysis. This may either be through a change in the amount the amount of enzyme used or differences in impacts from production. For example, integrated production of enzymes with bio-ethanol production has been shown potentially to reduce the cost and production impacts related to enzyme production (Johnson, 2016). However, it may also increase the impact depending on the feedstock used.
	-50%	

Figure 6-3 shows that the climate change impact for all of the MacroFuel biofuels are particularly sensitive to:

- Changes in seaweed yield (a -15% climate change impact with a 20% increase in seaweed yield to a 23% increase in impact with a 20% reduction in seaweed yield), and
- Changes in the lifetimes for growing equipment (up to a -28% change in climate change impact with a 50% increase in equipment lifetimes and up to a 86% increase in impact with a 50% decrease in equipment lifetimes).

This is consistent with the results presented in *Section 5*, which highlighted the growing equipment as the main contributor to the ‘cradle to grave’ climate change impact for the MacroFuel biofuels and demonstrates the importance of these inputs.

The sensitivity analyses show that the ‘cradle to grave’ climate change impact for the MacroFuel biofuels is much less sensitive to changes in the fuel use for seeding/harvesting (+/- 2 % change in impact with +/-50% change in input) and the impact from enzyme use / production (+/- 4 % change in impact with +/-50% change in input). This is due to the relatively small contribution from the seeding / harvesting and hydrolysis life cycle stages compared to the production and use of the growing equipment required to grow the seaweed feedstock. However, these changes could be more significant if the embedded climate change impact for production of the seaweed growing equipment was reduced.

6.3.3 Carbon Sequestration from Seaweed

Recent research suggests carbon in seaweed is sequestered in deep sea sediments and this may represent a long term sink of atmospheric CO₂ (Krause-Jensen & Duarte, 2016). The research suggests that up to 11% of carbon from net primary productivity of seaweed may be sequestered to the deep ocean (Krause-Jensen & Duarte, 2016). However, in the case of farmed seaweed, the crop is removed from the ocean and the aim is to maximise yields and reduce losses. To estimate the potential sequestration of carbon from farmed seaweed, we have assumed that 26% of seaweed growth is lost to the sea (Nielsen et al, 2014), and of this 13% will be sequestered in the deep ocean (Krause-Jensen & Duarte, 2016), resulting in approximately 7.5kg CO₂/ tonne seaweed (ww) sequestered in the deep ocean (see full calculation assumptions in *Annex B*).

Figure 6-2 Sensitivity analysis: Carbon sequestration

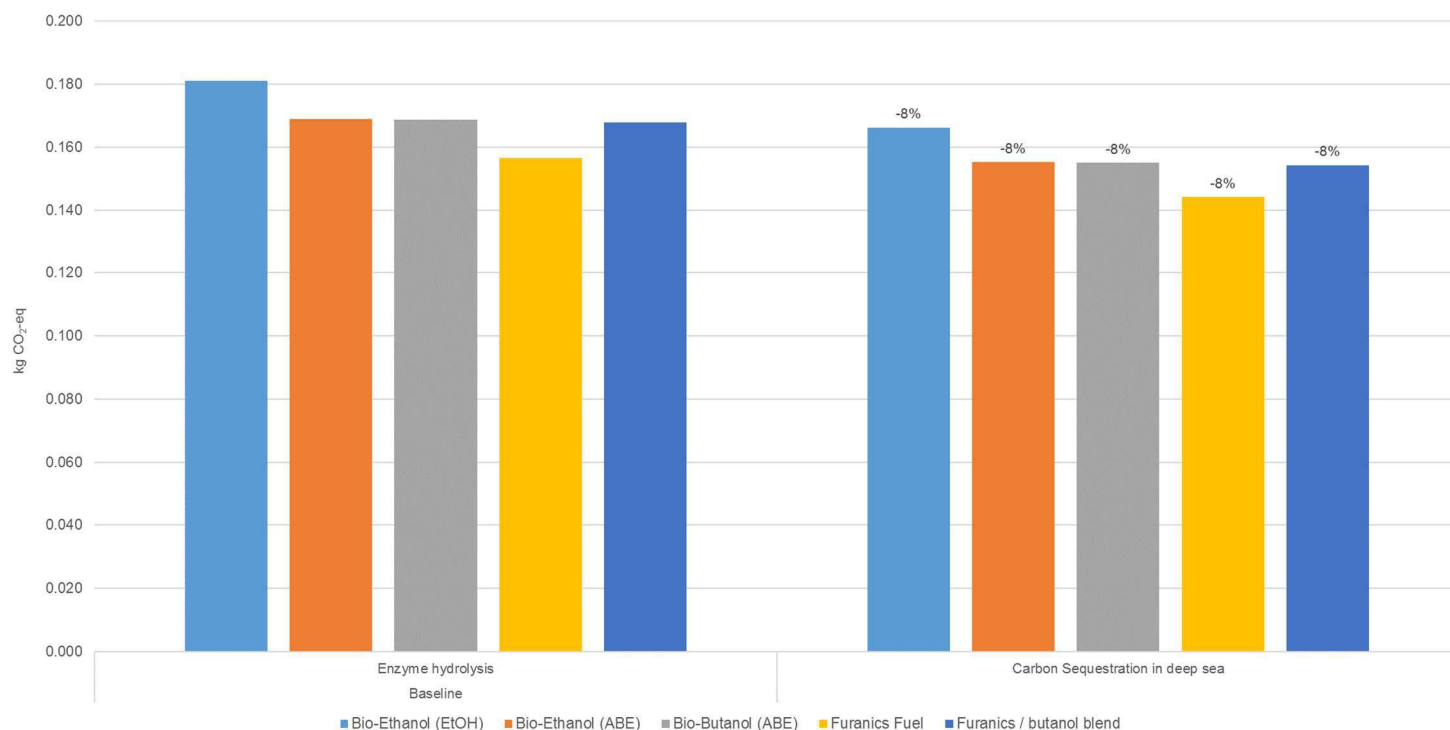
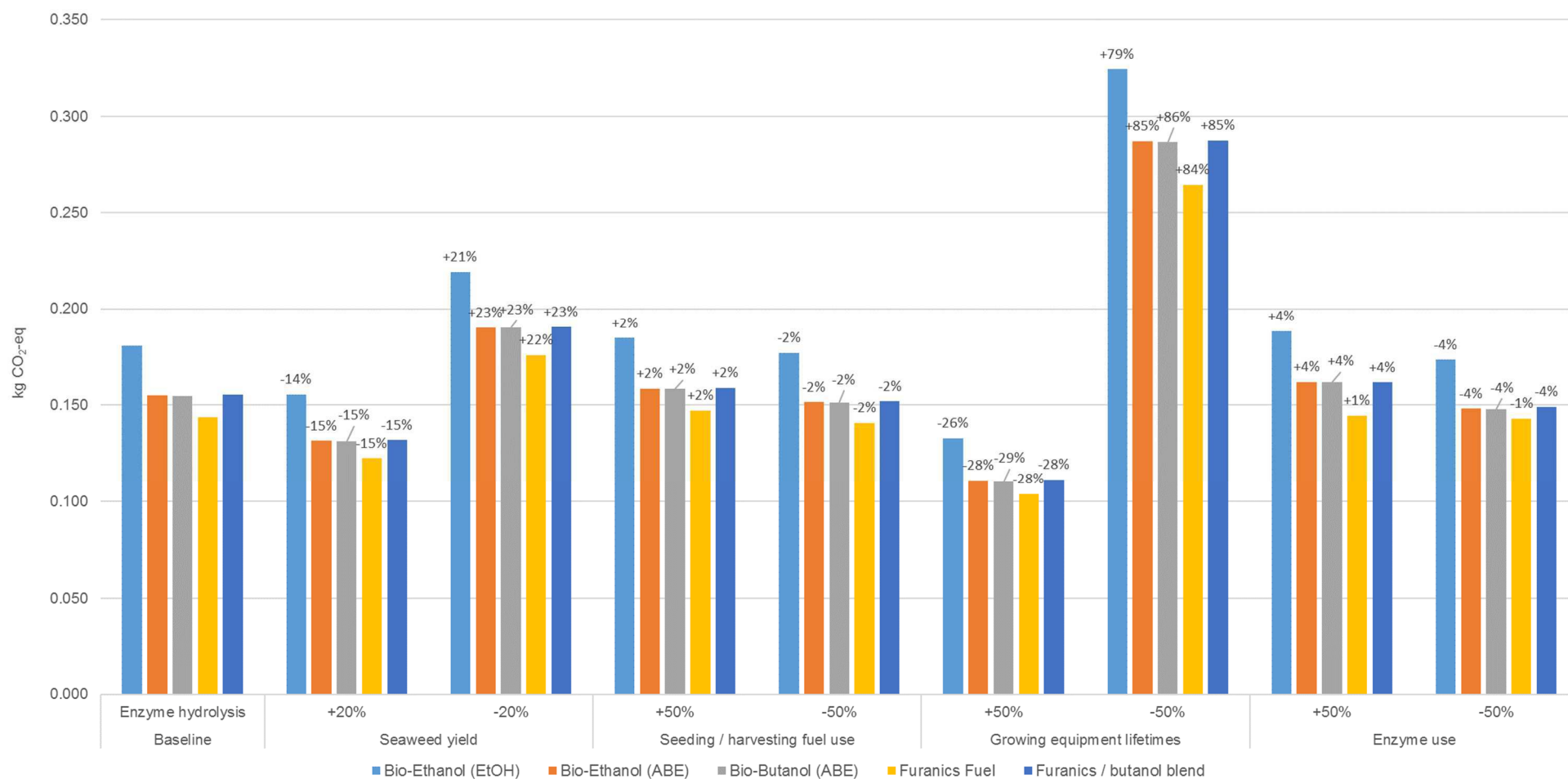


Figure 6-2 shows that the accounting for the sequestration of atmospheric CO₂ in the deep ocean reduces the 'cradle to gate' life cycle impact per MJ of the baseline MacroFuel biofuels by approximately 8%. This is a significant decrease and represents approximately 10% of the impact to produce seaweed. However, there is considerable uncertainty around the amount of atmospheric CO₂ which is sequestered in the deep ocean from seaweed growth globally. For example, there is a variation between 6% and 13% of carbon in seaweed based on the interquartile range quoted in Krause-Jensen & Duarte (2016). Furthermore, these global estimates largely consider wild growth of seaweed rather than cultivated seaweed, where the objective is to maximise yields and minimise losses. Therefore, the amount of carbon sequestered from cultivated seaweed systems may be less than these figures suggest.

Figure 6-3 Sensitivity analysis: Variation of key model values



6.3.4 Alternative Scenarios

The impact of the following alternative process configurations and material choices were assessed as sensitivity analyses. These represent potential improvements / variations to the production processes or processes with significant uncertainty that are not considered in the baseline scenarios.

The following sensitivity analyses were assessed, with details of the data used provided in *Annex B* (inventory tables).

1. **Recycled materials used for growing equipment:** the production of the growing equipment is the largest contributor to the climate change impact, accounting for approximately 68% - 79% of the 'cradle to grave' impact. In this sensitivity analysis it has been assumed that all of the growing equipment is produced from recycled feedstock ⁽¹⁾.
2. **Use of at sea storage bags for seaweed:** the MacroFuels project is evaluating the temporary storage of seaweed at sea after harvest in flexible storage bags (25 m³ each and made of PVC coated polyester), with the aim of ensuring increasing flexibility and reducing cost associated with the use of barges to transport harvested seaweed to the biorefinery. The use of the at sea storage bags means that the ensiling process can commence at sea as soon as the seaweed is harvested. This facilitates the use of smaller vessels for transporting the harvested seaweed to shore, by hauling a maximum number of the filled storage bags behind it (in a daisy chain fashion). To assess the potential impact of using this system, the use of the bag has been modelled and the significance of any additional impact is assessed. This change is assumed to have no impact on fuel use for the transport of seaweed to shore or the quality of the ensiled seaweed processed in the biorefinery.

Figure 6-4 shows the following:

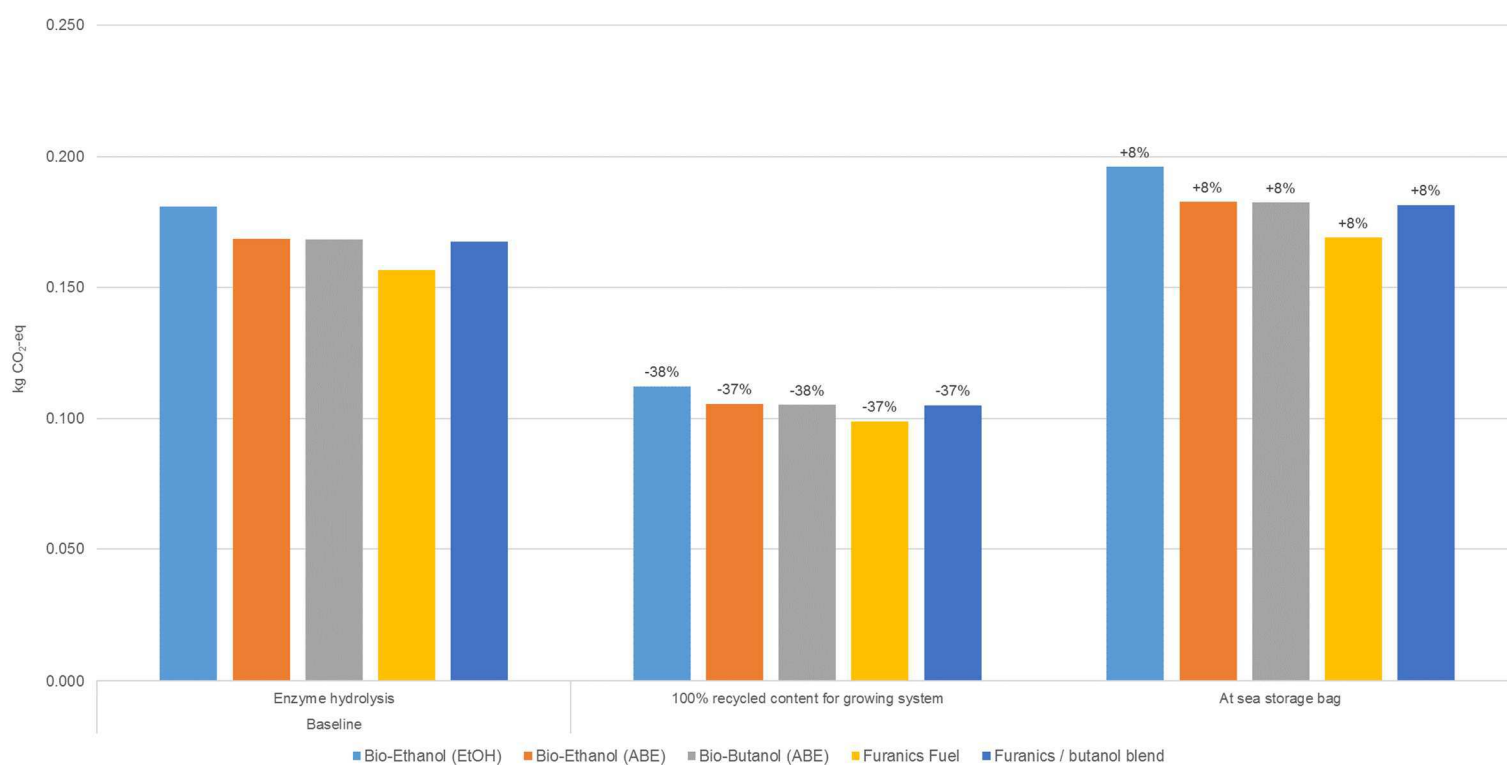
1. **Recycled materials used for growing equipment:** there is substantial reduction in the 'cradle to gate' climate change impact (37%-38% decrease) per MJ for all of the MacroFuel biofuels. This represents a reduction of approximately 50% in the impact of production of the growing equipment. This is driven by a 45% reduction in the impact related to the production

⁽¹⁾ This study uses the 'recycled content' approach for allocation of impacts from recycling (see *Section 3.6*) and the baseline assumption is that plastics used to produce sheetnets (PET), buoys (HDPE) and HDPE pipes are sourced from non-recycled feedstocks (i.e. directly from petrochemical feedstocks). In the baseline, Worldsteel data for primary production of steel and steel production including recycling for the sensitivity are used.

of the chain and screw anchors, which together are approximately 60% of the total baseline impact from the growing equipment. The use of 100% recycled content for the sheetnets and HDPE pipe result reduces the impact of these components by approximately 65%. Together, these account for approximately 20% of the baseline impact of the growing equipment. The results demonstrate the benefits of using recycled materials where possible.

2. **Use of at sea storage bags for seaweed:** the use of at sea storage bags increases the 'cradle to grave' climate change impact by approximately 8% for all of the MacroFuel biofuels, based on an assumed average lifetime of 5 years for the bags. This is a similar magnitude of impact to the production of galvanised steel screw anchors used in seaweed cultivation. However, this sensitivity analysis does not consider the potential benefit of avoiding biomass loss if transport of the harvested seaweed to the biorefinery by barge is delayed. There are also potential economic benefits from this system, because of the ability to use smaller boats to transport the biomass.

Figure 6-4 Sensitivity analysis: Alternative Scenarios



6.3.5 Sensitivity Analysis: Other Impact Categories

Annex C (Sensitivity analysis results) presents the sensitivity analysis results for climate change and all other environment impact categories assessed as part of the project. Trends in the sensitivity analysis results for all of the other impact categories are similar to those for climate change impact, except for the assessment of using recycled content to produce the growing equipment (see sensitivity analysis 1 in *Section 6.4*).

6.3.5.1 Recycled Materials Used for Growing Equipment

Results for the climate change impact show a substantial reduction in the 'cradle to gate' climate change impact (37%-38% decrease) in this sensitivity analysis. As shown in *Annex C*, reductions in impact of a similar or lesser magnitude are seen for all of the other impact categories assessed except for:

- Freshwater ecotoxicity (49%-90% increase);
- Freshwater eutrophication (18%-20% increase);
- Human toxicity(non-cancer) (11%-20% increase); and
- Ozone depletion (9%-24% increase).

The main reasons identified for the increases are as follows.

- Freshwater ecotoxicity: increased emissions of copper and zinc related to waste management / processing to recover the plastic recycle from municipal solid waste.
- Freshwater eutrophication: increased phosphate emissions from spoil from lignite mining associated with energy used for producing recycled plastic.
- Human toxicity(non-cancer): increased emissions of zinc and arsenic to water from the production of recycled HDPE.
- Ozone depletion: increased emissions of trichlorofluoromethane and 1,2-dichloro-1,1,2,2-tetrafluoroethane from the steel recycling process.

6.4 Benchmarking: Climate Change Impact

A key objective of this study is to benchmark the biofuels assessed under the MacroFuels concept project against current equivalent, conventional fossil-based fuels and available biofuels.

Details of the benchmark fossil based fuels and biofuels are shown in *Table 6-6*.

Table 6-6 Benchmark fossil based fuels and biofuels for the Macrofuel biofuels

Fuel	Process Description	Source
<i>Biofuels (ethanol)</i>		
Ethanol, sugar beet	No co-products, used in boiler	Section D, Annex 5, RED 2018
Ethanol, sugar beet	Biogas co-product, used in boiler	Section D, Annex 5, RED 2018
Ethanol, sugar beet	Biogas co-product, used in CHP	Section D, Annex 5, RED 2018
Ethanol, corn	No co-products, used in boiler	Section D, Annex 5, RED 2018
Ethanol, sugar cane	Not specified	Section D, Annex 5, RED 2018
Ethanol, wheat straw	Not specified	Section D, Annex 5, RED 2018
<i>Fossil Fuels</i>		
Petrol	Petrol, unleaded {RER} market	Ecoinvent 3.4
Diesel	Diesel {RER} market	Ecoinvent 3.4

The furanic fuel additive is a centane improver in diesel engines, providing performance improvements when used as a diesel additive. The furanic fuel additive may displace conventional fossil derived additives such as f 2-ethylhexyl nitrate. The furanic fuel has not been benchmarked against fossil based centane improvers, as this is beyond the scope of the functional unit considered in this study.

6.4.1 Benchmarking Against RED Sustainability Criteria

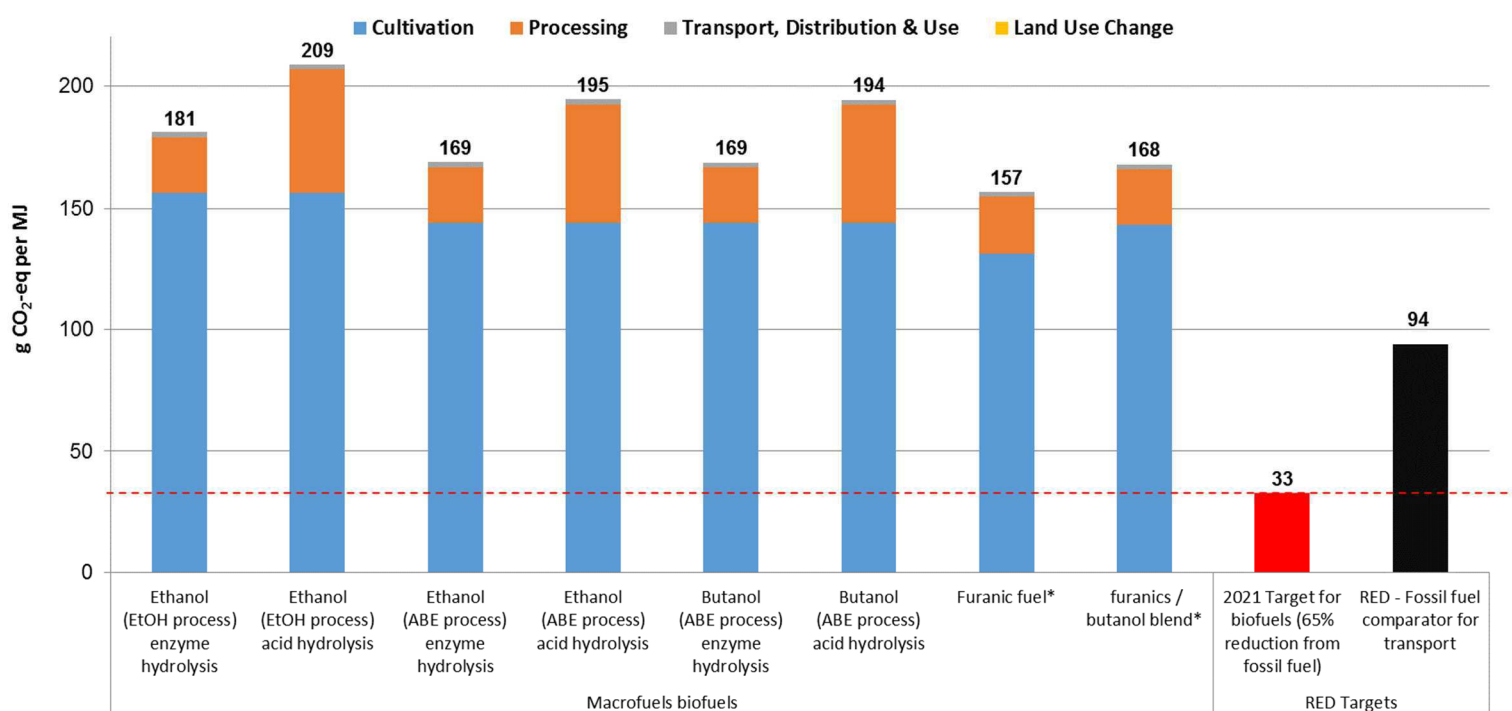
Figure 6-5 shows the MacroFuel biofuels compared to the sustainability criteria as specified in the RED. The sustainability criteria require a 65% GHG emission saving compared a fossil fuel comparator for transport fuels of 94 g CO₂eq/MJ. Thus, the full lifecycle GHG emissions from any biofuel produced to meet the targets of the RED must be less than 32.9 g CO₂eq/MJ.

The following are evident from *Figure 6-5*:

- As currently configured, none of the baseline MacroFuel concept biofuels meet the RED sustainability criteria, and their footprints are significantly greater than this (approximately five to six times higher).
- The climate change impact of all of the MacroFuel biofuels is greater than the fossil fuel comparator specified in the RED for transport fuels (> 94 g CO₂eq/MJ).

- The impact from seaweed cultivation alone for the MacroFuel biofuels is greater than the impact for the fossil fuel comparator.
- The contribution from biofuel processing for all of the butanol and ethanol produced via the acid hydrolysis route is greater than the RED sustainability criteria target in itself (> 33 g CO₂eq/MJ).
- The furanic fuel has the lowest climate change impact of all the MacroFuel biofuels (157 g CO₂eq/MJ).

Figure 6-5 Comparison of MacroFuel biofuels to RED sustainability criteria



*Note: butanol used in the production / blending of furanic fuels is assumed to be produced from seaweed by the ABE process, using enzyme hydrolysis. The contribution to each life cycle stage from the butanol reacted or blended with the furanic fuel has been added to the impact from each life cycle stage for the furanic fuel.

6.4.2 Benchmarking Against Fossil Fuels and Currently Available Biofuels

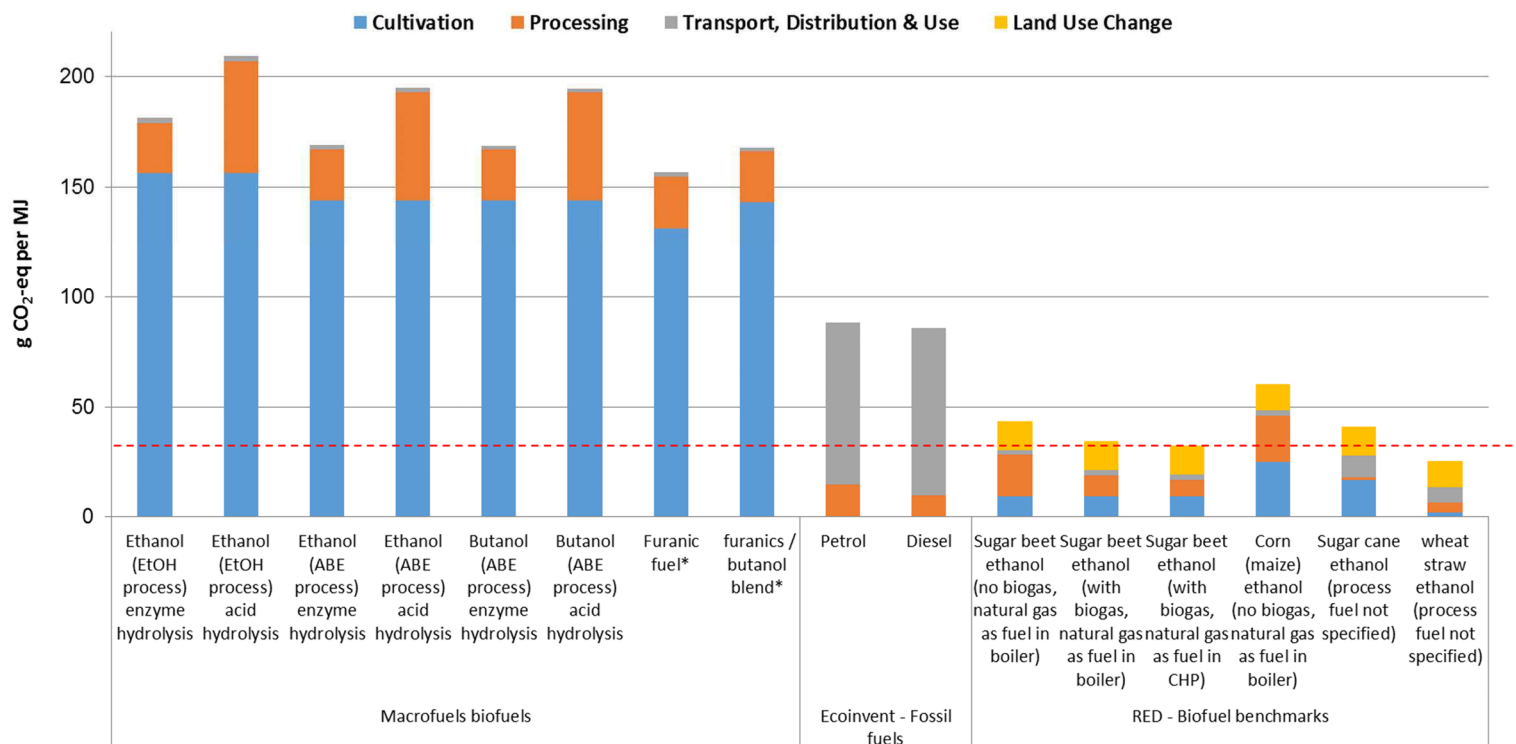
Figure 6-6 shows the MacroFuel biofuels compared to selected equivalent conventional, fossil-based fuels (from Ecoinvent 3.4 database) and currently available biofuels (average bio-ethanol from various feedstocks as defined in Annex V of RED). The results presented represent the ‘cradle to grave’ climate change impact and show the contribution from cultivation of feedstock, processing to biofuel and distribution and use of the product. The biofuels also show the potential impact from indirect land use change ⁽¹⁾, based on average values for each crop type as specified in Annex VIII of RED. As seaweed is grown in the sea, this potential impact is not relevant to the MacroFuels biofuels.

The following are evident from Figure 6-6.

- As the concept is presently configured, the baseline MacroFuel biofuels all have a significantly greater ‘cradle to grave’ climate change impact than the bio-ethanol produced from all the comparison bio feedstocks (approximately three to eight times higher).
- The cultivation stage for the baseline MacroFuel biofuels is the biggest driver of impact and requires significant mitigation.
- The ‘cradle to grave’ climate change impact of all of the MacroFuel concept biofuels is greater than petrol or diesel;
- All of the of the benchmark biofuels, except for corn (maize) ethanol, meet the RED sustainability criteria when no impact from indirect land use change is considered. When indirect land use change is considered, only sugar beet ethanol (with biogas as co-product and natural gas as fuel in CHP) and ethanol from wheat straw meet the RED sustainability criteria.
- The benchmarks highlight the benefits of co-production of biogas with ethanol and that the use of CHP can reduce this further.

⁽¹⁾ Indirect land use change (iLUC) can occur when land previously devoted to food or feed production is converted to produce biofuels, bioliquids and biomass fuels. In such cases, food and feed demand still needs to be satisfied, which may lead to the extension of agricultural land into areas with a high carbon stock, such as forests, wetlands and peat land, causing additional greenhouse gas emissions.

Figure 6-6 Comparison of MacroFuel biofuels to fossil fuel and biofuels



* Note: butanol used in the production / blending of furanic fuels is assumed to be produced from seaweed by the ABE process, using enzyme hydrolysis. The contribution to each life cycle stage from the butanol reacted or blended with the furanic fuel has been added to the impact from each life cycle stage for the furanic fuel.

The greater climate change impact for the baseline MacroFuel biofuels compared to the other biofuel benchmarks is a result of the large impact associated with production of the seaweed feedstock. Table 6-7 below compares the production of the seaweed feedstock to average values for the cultivation of sugar beet, maize and wheat, assessed as part of the BioGrace project. The BioGrace project was developed to provide robust default values to aid the calculation of GHG emissions from biofuel production to support assessment of the sustainability criteria described in the original version of Renewable Energy Directive (2009/28/EC).

Table 6-7 Comparison of climate change impact of seaweed to other biofuel feedstocks.

Feedstock	% dry weight	Cultivation impact		MJ of all co-products per kg (dw) (including all biomethane produced)
		gCO ₂ -eq/kg (ww)	gCO ₂ -eq/kg (dw)	
Seaweed ¹	13%	79	606	6.2 - EtOH process 6.3 - ABE Process 6.7 - Furanic fuel (unblended)
Sugar beet	25%	36	143	8.8
Maize (corn)	85%	297	349	9.4
Wheat	87%	308	356	9.0

Table 6-7 shows that while the climate change impact for the cultivation of seaweed per kg wet weight (ww) is lower than that for both maize and wheat (approximately four times less) it is approximately double the climate change impact of sugar beet. However, seaweed has a very high water content compared to the other biofuel feedstocks and it is the dry weight which can be converted into biofuels. When the climate change impact is compared on a dry weight basis, it is substantially greater (two to four times) for the seaweed than the other biofuel feedstocks.

Furthermore, the biofuel yield from feedstock has a large impact on the climate change impact for the biofuels. Table 6-7 shows that the energy yield from the biofuels assessed by the Biograce project of approximately 9 MJ per kg (dw) processed, with only ethanol as a product and no biogas production from residues. This compares to approximately 6.2 MJ per kg (dw) processed for the EtOH process and ABE process and 6.7 MJ per kg (dw) processed for the furanics fuel (unblended), with all biogas production from residues included. This shows that, in addition to greater climate change impact from the cultivation of the seaweed, the energy content of all of the fuel products produced under the MacroFuels concept is less than for the comparison biofuels.

¹ The results of the cradle to gate for seaweed production is shown in Annex D for all of the impact categories considered in this study.

6.5 Potential Options to Reduce Climate Change Impact

6.5.1 Improved scenario

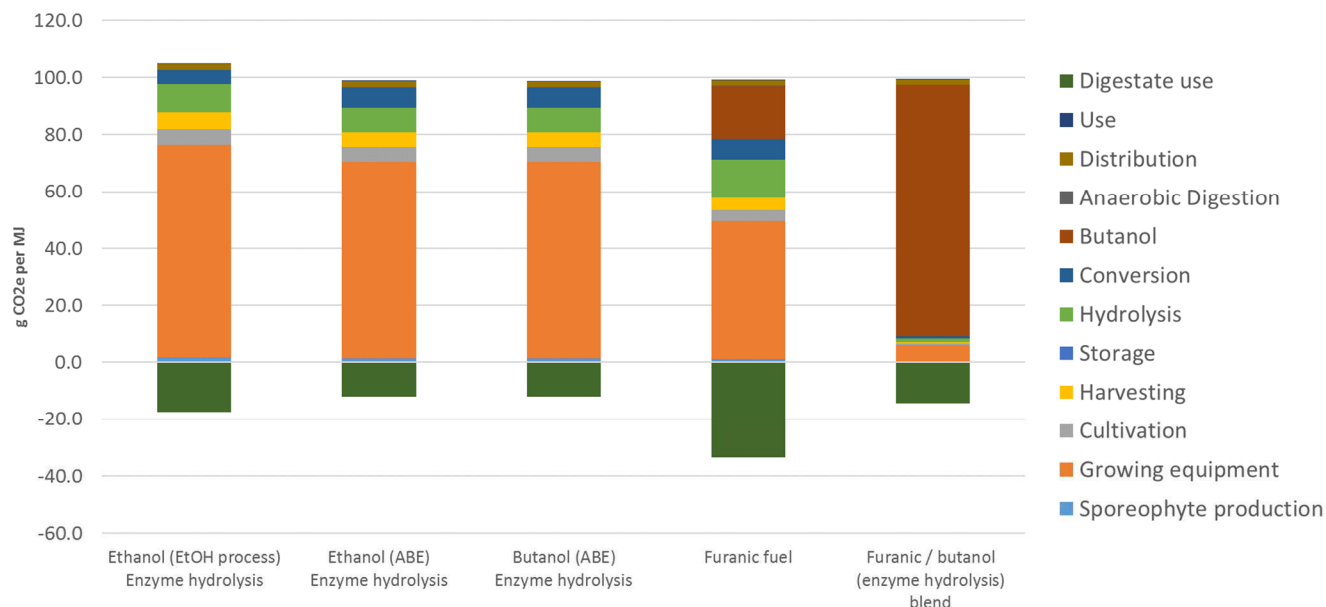
Based on the sensitivity analyses, an improved scenario has been developed to show the combined effect on the climate change impact for the MacroFuel biofuels if the following options are implemented:

- Use of recycled materials to produce growing equipment;
- Reduction in enzyme use in hydrolysis by 50%; and
- Receiving credit for digestate replacing inorganic fertilisers.

Table 6-8 Climate change impact with reduced impact production route compared to baseline

	Baseline (kgCO₂-eq/MJ)	Improved (kgCO₂-eq/MJ)	Percentage change from baseline
Ethanol (EtOH process) - enzyme hydrolysis	181	87	-52%
Ethanol (ABE) - enzyme hydrolysis	169	87	-49%
Butanol (ABE) - enzyme hydrolysis	169	86	-49%
Furanic fuel	157	65	-59%
Furanic / butanol (enzyme hydrolysis) blend	168	84	-50%

Figure 6-7 Applying potential options to reduce climate change impact for MacroFuel biofuels



Fejl! Henvisningskilde ikke fundet. Table 6-8 and Figure 6-7 show that the cradle to gate climate change impact is reduced by approximately 50% for all of the MacroFuel products. This ranges from 84-87 gCO₂-eq/MJ for ethanol, butanol and the furanics/butanol blend, but is significantly lower for the furanic fuel additive (65 gCO₂-eq/MJ). This is primarily a result of the larger credit for digestate replacing inorganic fertilisers. Without this credit, the climate change impact of the furanic fuel is similar to the other biofuels and so this result will be very sensitive to the assumptions made for the credit from digestate use, the quality of the digestate which can be produced and proximity to those markets which can use it.

Despite the reductions in impact, all of the MacroFuel biofuels, except for the unblended furanic fuel (with digestate credit), have a similar 'cradle to gate' climate change impact to that of petrol and diesel produced from fossil fuel sources and are significantly greater than the RED sustainability criteria target for transport fuels of 32.9 kgCO₂-eq/MJ and other biofuel currently available. This suggests that further reductions in the 'cradle to grave' climate change impact of the MacroFuel biofuels would be required to establish them as sustainable alternative to fossil fuels.

To achieve further reductions in the climate change impact for the MacroFuel biofuels the following would be required:

- Further reductions in the impact associated with the growing equipment used in cultivation; and
- Allowance for receiving credit for digestate replacing inorganic fertilisers.

6.5.2 Other Potential Environmental Improvements

Other opportunities to reduce the climate change impact from the biofuel production, which have not been assessed in this study include the following:

- Use of combined heat and power (CHP);
- Alternative cultivation systems; and
- Prioritisation of high value co-products from seaweed.

6.5.2.1 *Use of CHP in Biofuel Production*

The use of CHP to produce electricity, as well as process heat from the biogas co-product, could further reduce the climate change impact for the MacroFuel biofuels. Electricity generated from biogenic fuels from CHP may be used in the biofuel production process, thus avoiding embodied environmental impact from the use of grid electricity. CHP is typically more efficient than producing heat or electricity by itself, as heat losses to the environment are minimised.

When calculating GHG emissions under the RED sustainability criteria (Annex V, RED), excess electricity produced from CHP (i.e. electricity not used to produce the biofuel) may be exported to other users and a credit equal to the GHG emissions from producing the same amount of electricity in a power plant with the same fuel (e.g. natural gas), thus potentially reducing the climate change impact of producing the biofuel product. For the MacroFuels biofuels, while CHP could provide a reduction in the climate change impact, it is also important to decrease the embodied GHG emissions of the feedstock seaweed.

6.5.2.2 *Investigate Alternative Cultivation Systems*

Production of the materials used in the growing system has a major impact on the GHG emissions associated with producing the MacroFuel biofuels and also in other environmental impact categories. This is primarily as a result of emissions and energy use from the production of galvanised steel chain and HDPE plastic pipes and buoys. Options to reduce the use of chain could be investigated, including:

- Removal of chain from inside HDPE and its replacement with alternative materials to keep the sheetnets submerged at the correct depth;
- Partial replacement of chain with rope to connect the cultivation segments to buoys, anchors and dampening blocks; and
- Alternative systems which do not use horizontal sheetnets, such as vertically oriented sheetnets or long line rope based systems.

For any of these options, further assessment would need to be undertaken to confirm if the system would deliver acceptable seaweed yields, be robust enough to work in the open sea and if the potentially shorter lifetimes of the equipment, made from lower impact materials like rope, would offset gains in the reduction of the impact from the production of the alternative materials.

6.5.2.3 *Prioritisation of High Value Co-Products from Seaweed*

In addition to the sugars and carbohydrates in seaweed which can be converted into biofuels, seaweed also contains other materials which may be extracted as useful products, potentially with significant value. These include protein for use in food for animals and humans or alginates for use in cosmetics or pharmaceuticals. This is supported by Horn, who suggests that bioethanol production may only be economically viable if integrated with industrial alginate production (Horn 2009). This idea has been taken further, with the development of the concept of the cascading sustainable bio-refinery, which requires the product with the highest value to be made first and then that with the second highest value and so on (Balina et al, 2017). In practice, this may require the extraction of high value products prior to the production of biofuels from the remaining residues. This approach would require the use of alternative allocation methods than allocation by energy content, as required by RED and implemented in this study, in order better to reflect the value of the multiple types of co-products that may be produced.

7 CONCLUSIONS

The main objectives of this study were to:

- Conduct a 'cradle-to-grave' environmental life cycle assessment (LCA) of the MacroFuels concept, in order to determine the environmental impact of producing biofuels from seaweed for use as transport fuels;
- Identify hotspots and reduction opportunities; and
- Benchmark the full life cycle GHG emissions (climate change impact) against equivalent transport fuels produced from fossil fuel sources / other biofuel feedstocks using the sustainability criteria for GHG emissions under Renewable Energy Directive (2018/2001).

7.1 Results

7.1.1 Main Environmental Impacts

The production of growing equipment for seaweed cultivation and the hydrolysis step are the main contributors to the environmental impact of MacroFuel biofuel products. In particular, the growing equipment makes a significant contribution to the climate change, particulate matter, acidification, terrestrial eutrophication marine eutrophication, human toxicity (cancer), photochemical ozone creation and mineral, fossil & renewable resource depletion impact categories. Hydrolysis is particularly significant when considering ozone depletion, human toxicity (non-cancer), freshwater ecotoxicity and freshwater eutrophication.

Within the growing equipment life cycle stage, the chain used to secure the sheetnets to the anchors and buoys and keep them underwater accounts for 40% or more of the impact from the growing equipment for all of the environmental impact categories except for: human toxicity (cancer effects); freshwater eutrophication; and freshwater ecotoxicity. For these impact categories, the contribution of producing buoys and HDPE pipe account represents more than 75% of the impact of the growing equipment.

For ethanol and butanol products, production via acid hydrolysis has a greater impact than using enzyme hydrolysis for 10 out of 13 impact categories, including climate change. For human toxicity (non-cancer effects), marine eutrophication and freshwater ecotoxicity impact categories, the impact of enzyme hydrolysis is greater.

7.1.2 Benchmarking GHG Emissions

A key objective of this study is to benchmark the biofuels assessed under the MacroFuels project against equivalent conventional, fossil-based fuels and currently available biofuels, and the sustainability criteria for GHG emissions under Renewable Energy Directive (2018/2001) (RED).

The benchmarking results showed the following:

- None of the baseline MacroFuel biofuels meet the RED sustainability criteria (32.9 g CO₂eq/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 CO₂eq/MJ);
- The 'cradle to grave' climate change impact of all the baseline MacroFuel biofuels is greater than petrol or diesel; and
- The MacroFuel biofuels all have a significantly greater 'cradle to grave' climate change impact than the bio-ethanol produced from all of the comparison bio-feedstocks.

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

- Seaweed produced under the MacroFuels concept has a greater climate change impact per kg (dw) of feedstock than the sugar beet, 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-feedstocks on a dry weight basis.

7.2 Recommendations

Sensitivity analyses were completed to identify the sensitivity of key modelling assumptions, to assess alternative scenarios and data and their potential to reduce the climate change impact of the MacroFuel biofuels. The main opportunities to reduce the climate change impact for the MacroFuels biofuels are:

1. Reduce growing material requirements;
2. Extend growing material lifetimes;
3. Increase biomass yield;

4. Maximise recycled content for materials used in growing equipment;
5. Use enzyme hydrolysis rather than acid hydrolysis to produce ethanol or butanol via fermentation;
6. Reduce the amount of enzyme required in hydrolysis; and
7. Receiving credit for digestate replacing inorganic fertilisers.

A combined improvement scenario was developed based on opportunities 4, 5, 6 & 7. This showed the potential for reductions in climate change impact by approximately 50% for ethanol and butanol and 59% for the furanic fuel.

Other factors which could reduce the climate change impact of the Macrofuels biofuels include:

- Sequestration of carbon from seaweed in the deep sea;
- Alternative designs for the cultivation system to reduce the amount of chain used;
- Use of CHP in biofuel production; and
- Prioritisation of high value co-products from seaweed in bio-refineries with residues used for energy production.

The improvement options discussed here have the potential to deliver MacroFuel biofuels with significantly lower climate change impact than conventional fossil fuels.

When conducting future assessments of pilot or large scale production, it is recommended that primary data are sought for:

- Manufacturing, use and disposal of growing equipment;
- Operation of machinery during cultivation and harvesting; and
- Supply of materials used in hydrolysis and conversion.

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9 REFERENCES

- K. Balina, F. Romagnoli & D. Blumberga (2017), Seaweed biorefinery concept for sustainable use of marine resources , Energy Procedia 128 (2017) 504–511
- BioGrace, 2012, Publishable final report, www.biograce.net
- BioGrace-I calculation rules, 2015, version 4d, www.biograce.net
- S. Burg, A.Dujin, H.Bartelings, M.Krimpen and M.Poelman (2016) The economic feasibility of seaweed production in the North Sea, Aquaculture Economics & Management 20, p. 235-252
- COM(2016)767 Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast). Available at: https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf (Accessed: 05 December 2016).
- J.W. Dijkstra, D.F. Meyer and S.D. Rios (2019) Techno-economic evaluation and health and safety risks, MacroFuels deliverable 6.2
- Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2011/77/EC and 2003/30/EC, Official Journal of the European Union L140 5 June 2009.
- Directive 2009/30/EC amending Directive 98/70/EC as regards specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC, Official Journal of the European Union L140 5 June 2009.
- Directive (EU) 2015/1513 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources, Official Journal of the European Union L239 15 September 2015.
- Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, Official Journal of the European Union L328/82 21 December 2018
- Finanzen. (2018). Ethanolpreis. from <https://www.finanzen.net/rohstoffe/ethanolpreis>
- J. Fry and S. Aumonier (2016) Techno-economic and sustainability assessment – Criteria settings, MacroFuels deliverable 6.1
- J. Fry, J. Joyce, S. Aumonier, (2012) Carbon footprint of seaweed as a biofuel, Marine estate research report, The Crown Estate

Groenendaal, B., Vandendaele, P., & Vroman, F. (2017). Turnkey seaweed farms: from an European project to a sound business.

Horn (2009). Seaweed biofuels. Production of biogas and bioethanol from brown macroalgae. VDM Verlag Dr. Müller.

ICIS. (2018). Chemical profile reports 2013-2018. ICIS chemical business.

ISO 14040 (2006). *Environmental Management – Life Cycle Assessment – Principles and Framework*. International Organization of Standardization.

ISO 14044 (2006). *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. International Organization of Standardization.

Johnson, E (2016), Integrated enzyme production lowers the cost of cellulosic ethanol, Biofuels, Bioproducts, Biorefining - 10:164–174

D. Krause-Jensen and C. M. Duarte, Substantial role of macroalgae in marine carbon sequestration, Nature Geoscience, 2016, DOI: 10.1038/NGEO2790

H. L. MacLean and S. Spatari (2009), The contribution of enzymes and process chemicals to the life cycle of ethanol Environmental Research Letters 4 (2009) 014001 (10pp)

MacroFuels deliverable 2.4 (2019), Efficiency of enzymes applied in the pre-treatment of seaweed,

M. Nielsen, D. Krause-Jensen, B. Olesen, R. Thinggaard, P. Christensen, A. Bruhn (2014), Growth dynamics of *Saccharina latissima* (Laminariales, Phaeophyceae) in Aarhus Bay, Denmark, and along the species' distribution range, Marine Biology Volume 161, Issue 9, pp 2011–2022

Rocca, S., Agostini, A., Giuntoli, J. and and Marelli, L. (2015) *Biofuels from algae: technology options, energy balance and GHG emissions; Insight from a literature review*. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC98760/algae_biofuels_report_21122015.pdf (Accessed: 21 November 2016).

Schoots, K. P. H., et. al. . (2015). Nationale Energieverkenning 2015: ECN/PBL.

Sioen (2015, 2015). [Sioen WebSite Newsflash: AT SEA TURNKEY FARM].

Tian M, McCormick R, Luecke J, Jong E, Van der Waal J. C, Gerard P. M, (2017) *Anti-knock quality of sugar derived levulinic esters and cyclic ethers*, Fuel 202 pp 414 – 425.

10 ABBREVIATIONS AND GLOSSARY

10.1 Abbreviations

ABE	Acetone-butanol-ethanol
EtOH	Ethanol fermentation
IBE	Isopropanol-butanol-ethanol
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
RED	Renewable Energy Directive (2018/2001/EC)
S-LCA	Social life cycle assessment

10.2 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.

Annex A: *Environmental impact categories*

The following are descriptions of the environmental impact categories assessed in this study.

A1 Climate change

Climate change is a measure of the adverse environmental effect caused by man-made emissions of greenhouse gases, which cause heat to be trapped in the atmosphere and result in a temperature rise of the Earth's surface. Different gases are given different characterization factors that have been developed by the Intergovernmental Panel on Climate Change (IPCC), in an aim to quantify the climate change impact of different emissions. These characterization factors are given in terms of carbon dioxide equivalent (CO₂-eq).

On calculating CO₂ equivalents, the residence time of the gases in the troposphere is taken into account and models for time periods of 20, 50 and 100 years have been developed. Commonly, a time horizon of 100 years is used, as this reflects the long-term impacts of climate change. This was also chosen for this project.

For the purposes of this study, the substances contributing to climate change and their corresponding characterisation factors (also known as Global Warming Potential, GWP) were based on IPCC 2007 data. The contribution to climate change was calculated by summing the products of the amount of each emitted harmful material (m_i) and the corresponding characterization factor (GWP_i) as expressed in the following equation:

$$\text{Climate change} = \sum(m_i \times \text{GWP}_i)$$

Climate change and biogenic carbon

There are different approaches to calculating climate change impacts related to biogenic carbon. The approaches can be described as follows.

a) Accounting for carbon uptake: the biogenic CO₂ uptake is included in the calculations. During the growth phase of renewable materials (e.g. trees), CO₂ from the atmosphere is absorbed and converted through photosynthesis. This is accounted for in the calculation through a negative characterization value. At the end of the material's life, the carbon stored in the material is released again. This is accounted for in the calculation through a positive characterization value.

b) Assuming carbon neutrality: the uptake of CO₂ during the growth phase and the emission of CO₂ at end of life are assumed to counterbalance one another. As such, the uptake and emission of CO₂ are disregarded in the calculations.

In this study, approach b) was applied.

Global warming potentials for carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are the same as those specified in the RED and so facilitate comparison with benchmarks outlined with RED.

A2 Ozone depletion

Ozone depletion refers to the destruction of the ozone layer in the stratosphere. The ozone layer is crucial to life as it absorbs harmful UV radiation from the sun. This radiation can cause increased human health risk and have negative impacts on plant life and aquatic ecosystems if it reaches the troposphere. Chlorine from chlorofluorocarbons (CFCs) and bromine from halons act as ozone depleting substances and decrease the amount of ozone in the atmosphere.

Ozone depletion is measured in terms of the capacity for an emission to reduce ozone in the stratosphere relative to the ozone reduction potential of trichlorofluoromethane (CFC-11) as a baseline. This is commonly expressed in terms of kilograms of CFC-11 per kilogram of emission of a substance. The significance of Ozone layer depletion has reduced with the effectiveness of the Montreal protocol in reducing emissions of ozone depleting substances.

A3 Human toxicity (cancer effects and non-cancer effects)

Human toxicity is a measure of the impact that chemicals that are emitted to the environment have on human health. The impact is split between cancer and non-cancer effects.

Some substances are poisonous to humans and can result in sickness or death through direct contact. Other substances can enter the food chain by accumulating in the living organisms that we eat (e.g. metals in fish) and, due to their properties, cause health effects.

Models that are used to calculate a substances human toxicity potential are based on: the environmental media (air, water, soil etc.); behaviour (e.g. movement between media, degradation, transformation, persistence in the food chain etc.); normal exposure (predicted daily intake) levels; and its toxicity on exposure.

The units of each toxic substance are converted to a common reference unit, for comparison purposes. The reference unit for human toxicity is the Comparative Toxic Unit for Humans (CTUh), expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kg).

A4 Particulate matter

Particulate matter (PM) refers to minute pieces of solid or liquid matter suspended in the atmosphere. Particulate matter can be anthropogenic or natural and can adversely affect human health and also have impacts on climate and precipitation. Particle pollution includes primary PM (PM_{2.5} and PM₁₀) and secondary PM (incl. creation of secondary PM due to SO_x, NO_x and NH₃ emissions) and CO.

The size of particles is directly linked to their potential for causing health problems. Once inhaled, the smallest particles can affect the heart and lungs and cause serious health effects. Respirable particles with a diameter of less than $10\mu\text{m}$ are referred to as PM_{10} . Fine particles with a diameter of less than $2.5\mu\text{m}$ are referred to as $\text{PM}_{2.5}$.

Particle impacts are reported as an expression of the potential contribution to particulates in the atmosphere. This is reported in kilograms of $\text{PM}_{2.5}$ equivalents (kg $\text{PM}_{2.5}$ eq), as the smallest particles are those of most concern to human health.

A5 Photochemical ozone formation

Photochemical ozone formation is a measure of the adverse effects from the formation on low-level ozone and other photo-oxidants. These are formed through a complex reaction pattern involving sunlight and nitrogen oxides (NO_x) with certain air pollutants, such as volatile organic compounds (VOCs), nitrogen oxides (NO_x) and carbon monoxide (CO).

Photochemical Ozone Creation Potential (POCP) is calculated from the change in ozone concentration in a set volume of air with the introduction of the emission of a substance relative to the change in emission of ethylene. The reference unit used for photochemical oxidation is kilograms of non-methane volatile organic compounds (kg NMVOC) per kilogram of emissions. This is calculated based upon a ratio of the POCP for ethylene.

A6 Acidification

Acidification refers to sulfur, nitrogen and phosphorous compounds being deposited in soil and water, which causes a change in acidity. Any change from the natural pH can have detrimental effects on plant and aquatic life. Some common emissions that contribute to acidification include nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonia (NH_3). The ILCD method calculates characterization factors for acidification based upon molecules of hydrogen equivalents (molc H^+ eq).

A7 Terrestrial eutrophication

Terrestrial eutrophication measures the enrichment of terrestrial ecosystems with the macronutrients N and P. The characterisation model is based on the stoichiometry given by a ratio between N and P, which is derived from the average composition of algae. The eutrophication potential is given in equivalents of molecules of nitrogen (molc N-eq).

A8 Freshwater eutrophication

Eutrophication is defined as nutrient enrichment (typically from algae growth) in an aquatic environment, resulting in excess consumption and hence depletion of oxygen from the environment. This nutrient pollution is typically generated in aquatic environments from phosphorous or nitrogen compounds through discharges from sewage treatment works and storm water run-off of fertilizers or manure. Only phosphorous and nitrogen compounds are characterised in this impact category.

Typically, in freshwater ecosystems in Europe, phosphorous compounds are the limiting factor in eutrophication of an environment. As a result, freshwater eutrophication reflects phosphorous compound emissions and is expressed in equivalents of kilograms of phosphate (kg P eq) for freshwater ecosystems.

A9 Marine eutrophication

In marine ecosystems, nitrogen compounds are the limiting factor in eutrophication of an environment. As a result, marine eutrophication-reflects nitrogen emissions and are expressed in equivalents of kilograms of nitrogen (kg N eq) for marine ecosystems.

A10 Freshwater ecotoxicity

Aquatic toxicity is a measure of the impact that chemicals emitted by human activities have on aquatic ecosystems and the organisms that live in them.

Models are used to calculate aquatic toxicity potential, and are based on the predicted concentration of the substance in the water and the effect factor, which is the toxic effect to organisms of the substance.

The toxic properties of each substance are converted to common reference units to enable comparison. For freshwater ecotoxicity, the reference unit is expressed as Comparative Toxic Unit for ecosystems (CTUe), expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m³ year/kg).

A11 Water resource depletion

Water consumption is becoming of increasing significance globally with regions experiencing extremes of water flow, from droughts to floods. Due to the difficulty in transporting water to affected areas, the need to assess and minimize the water consumption of a product or service over its lifetime is essential.

The ILCD method for water depletion considers the consumption of fresh water from lakes, rivers, wells and of unspecified natural origin. Additionally, cooling water, process and turbine water use are included in the method. The method takes account of six levels of regional scarcity.

Water resource depletion is expressed in cubic meters of water equivalent (m³ water eq).

For water consumption to be considered as an environmental impact requires local characterisation factors that take into account water scarcity and local pressures. With the increasing interest in water resources, it is expected that water resource impact methods will be developed further in the near future.

A12 Mineral, fossil & renewable resource depletion

Resource depletion is the over-consumption of resources, ie faster than they can be replenished. It is a measure of the scarcity of the raw materials consumed during the lifetime of the system considered. It is expressed in units of antimony equivalents.

Annex B: Inventory Tables

Table B - 1 MacroFuels product systems studied and corresponding lower heating value

Product systems	Lower heating value (MJ/kg)	Source
Ethanol (EtOH process - acid hydrolysis);	27	RED annex III
Ethanol (EtOH process - enzyme hydrolysis);	27	RED annex III
Ethanol (ABE process - acid hydrolysis);	27	RED annex III
Ethanol (ABE process - enzyme hydrolysis);	27	RED annex III
Butanol (ABE process - acid hydrolysis);	33	RED annex III
Butanol (ABE process - enzyme hydrolysis);	33	RED annex III
Furanics fuel additive	31.2	See Table B2 below
Furanics fuel (10%) / bio-butanol (90%) blend	32.5	See Table B2 below

Table B - 2 Composition of Furanic Fuel additive and Furanic Fuel / butanol blend and corresponding lower heating values

Compound	Furanic Fuel additive	Furanic fuel / butanol blend	Lower heating value (MJ/kg)	Source for LHV
Water	1%	1%	-2.44	
2-MethylTetraHydroFuran	38%	4%	34	Aspen plus database
Furfuryl-Alcohol	14%	2%	24.6	Aspen plus database
butyl tetrahydrofurfuryl ether	19%	2%	30.7	ethyl tetrahydrofurfuryl ether (ETE) used as a proxy (Tian et al, 2017) ⁽¹⁾ .
tetrahydrofurfuryl dibutyl acetal	5%	1%	30.7	ethyl tetrahydrofurfuryl ether (ETE) used as a proxy (Tian et al, 2017).
Toluene	3%	0.3%	40.5	Aspen plus database
Levulinic acid	3%	0.0%	24.6	assumed to have the same lower heating value as Furfuryl-Alcohol
Butanol	0.0%	88%	33	RED annex III
Other compounds dissolved in butanol	17%	2%	33	assumed to have the same lower heating value as butanol

⁽¹⁾ Tian M, McCormick R, Luecke J, Jong E, Van der Waal J. C, Gerard P. M, (2017) Anti-knock quality of sugar derived levulinic esters and cyclic ethers, Fuel 202 pp 414 – 425.

Table B - 3 Inventory data table for seaweed growing equipment

Component	Unit	Amount per hectare	Total weight per ton seaweed (kg ww)	Lifetime (years) ⁽¹⁾
Sheetnets	no.	272	4.00	5
Buoys (incl. marker buoys)	no.	679	32.6	10
Chain 10mm	Metres	9680	73.6	5
Hooks and shackles	no.	1495	3.65	10
Dampening blocks	no.	136	299	10
screw anchor	no.	72	28.9	10
Tubing (incl. spreader bars)	Metres	7840	54.9	10

Design of the seaweed cultivation system was based on a concept published in open literature (Groenendaal, Vandendaele, & Vroman, 2017; Sioen, 2015).

⁽¹⁾ Personal communication with Bert Groenendaal, SIOEN, May 2019.

Table B - 4 Process inventory for the ethanol fermentation process (EtOH process) using acid hydrolysis

Flow Name	unit	Amount per tonne of wet seaweed	Amount per tonne of dry seaweed	Source
Inputs				
Water	kg	1130	8692	Macrofuels deliverable 6.2
Hydrochloric acid	kg	37.3	287	Macrofuels deliverable 6.2
Diammonium phosphate	g	915	7038	Macrofuels deliverable 6.2
Sodium hydroxide	kg	30.4	234	Macrofuels deliverable 6.2
Water	kg	130	1000	Macrofuels deliverable 6.2
Air	dm3	116	891	Macrofuels deliverable 6.2
Electricity	kWh	5.89	45.3	Macrofuels deliverable 6.2
Outputs				
Bio-ethanol	kg	7.95	61.1	Macrofuels deliverable 6.2
Total Biogas production (26% methane)	kg	44.6 (11.6)	343 (89.2)	Macrofuels deliverable 6.2
Process biogas (26% methane)	kg	22.7 (5.90)	175 (45.5)	Macrofuels deliverable 6.2
Export biogas (26% methane)	kg	21.8 (5.69)	168 (43.7)	Macrofuels deliverable 6.2
Digestate (N 0.51%) (P 0.10%) (K 0.17%)	kg	190	1458	Macrofuels deliverable 6.2
Waste water - Filtration	kg	1796	13813	Macrofuels deliverable 6.2
Waste water - Purification	kg	13.1	101	Macrofuels deliverable 6.2
Waste water - AD	kg	71.7	551	Macrofuels deliverable 6.2
Flue gas	m3	150	1151	Macrofuels deliverable 6.2
Storage vent emissions	kg	0.031	0.24	Macrofuels deliverable 6.2
Fermentation vent emissions	kg	8.2	63	Macrofuels deliverable 6.2

Table B - 5 Process inventory for the ethanol fermentation process (EtOH process) using enzyme hydrolysis

Flow Name	unit	Amount per tonne of wet seaweed	Amount per tonne of dry seaweed	Source
Inputs				
Water	kg	1000	8692	Macrofuels deliverable 6.2
Enzymes	kg	1.30	10.0	Macrofuels deliverable 2.4
Diammonium phosphate	g	915	7038	Macrofuels deliverable 6.2
Water	kg	130	1000	Macrofuels deliverable 6.2
Air	dm3	116	891	Macrofuels deliverable 6.2
Electricity	kWh	5.89	45.3	Macrofuels deliverable 6.2
Outputs				
Bio-ethanol	kg	7.95	61.1	Macrofuels deliverable 6.2
Total Biogas production (26% methane)	kg	44.7 (11.6)	344 (89.4)	Macrofuels deliverable 6.2
Process biogas (26% methane)	kg	22.8 (5.93)	175 (45.5)	Macrofuels deliverable 6.2
Export biogas (26% methane)	kg	21.9 (5.69)	169 (43.9)	Macrofuels deliverable 6.2
Digestate (N 0.51%) (P 0.10%) (K 0.17%)	kg	190	1458	Macrofuels deliverable 6.2
Waste water - Filtration	kg	1796	13813	Macrofuels deliverable 6.2
Waste water - Purification	kg	13.1	101	Macrofuels deliverable 6.2
Waste water - AD	kg	71.7	551	Macrofuels deliverable 6.2
Flue gas	m3	150	1151	Macrofuels deliverable 6.2
Storage vent emissions	kg	0.031	0.24	Macrofuels deliverable 6.2
Fermentation vent emissions	kg	8.2	63	Macrofuels deliverable 6.2

Table B - 6 Inventory data for the ABE scenario using acid hydrolysis

Flow Name	unit	Amount per tonne of wet seaweed	Amount per tonne of dry seaweed	Source
Inputs				
Water	kg	1499	11527	Macrofuels deliverable 6.2
Hydrochloric acid	kg	37.3	287	Macrofuels deliverable 6.2
Diammonium phosphate	kg	2.51	19.3	Macrofuels deliverable 6.2
Sodium hydroxide	kg	30.4	234	Macrofuels deliverable 6.2
Air	dm3	101	778	Macrofuels deliverable 6.2
Electricity	kWh	5.55	42.7	Macrofuels deliverable 6.2
Outputs				
Bio-acetone	kg	3.17	24.4	Macrofuels deliverable 6.2
Bio-butanol	kg	7.23	55.6	Macrofuels deliverable 6.2
Bio-ethanol	kg	1.12	8.65	Macrofuels deliverable 6.2
Total Biogas production (26% methane)	kg	34.2 (8.89)	263 (68.4)	Macrofuels deliverable 6.2
Process biogas (26% methane)	kg	20.2 (5.25)	155 (40.3)	Macrofuels deliverable 6.2
Export biogas (26% methane)	kg	14.0 (3.64)	108(28.1)	Macrofuels deliverable 6.2
Digestate (N 0.32%) (P 0.09%) (K 0.09%)	kg	432	3325	Macrofuels deliverable 6.2
Waste water - Filtration	kg	1809	13914	Macrofuels deliverable 6.2
Waste water - Purification	kg	18.4	142	Macrofuels deliverable 6.2
Waste water - AD	kg	244	1873	Macrofuels deliverable 6.2
Flue gas	m3	121	933	Macrofuels deliverable 6.2
Storage vent emissions	kg	0.031	0.24	Macrofuels deliverable 6.2
Fermentation vent emissions	kg	19.7	152	Macrofuels deliverable 6.2

Table B - 7 Inventory data for the ABE scenario using enzymatic hydrolysis

Flow Name	unit	Amount per tonne of wet seaweed	Amount per tonne of dry seaweed	Source
Inputs				
Water	kg	1499	11527	Macrofuels deliverable 6.2
Enzymes	kg	1.30	10	Macrofuels deliverable 2.4
Diammonium phosphate	kg	2.51	19.3	Macrofuels deliverable 6.2
Water	kg	499	3835	Macrofuels deliverable 6.2
Air	dm3	101	778	Macrofuels deliverable 6.2
Electricity	kWh	5.55	42.7	Macrofuels deliverable 6.2
Outputs				
Bio-acetone	kg	3.17	24.4	Macrofuels deliverable 6.2
Bio-butanol	kg	7.23	55.6	Macrofuels deliverable 6.2
Bio-ethanol	kg	1.12	8.65	Macrofuels deliverable 6.2
Total Biogas production (26% methane)	kg	34.2 (8.89)	263 (68.4)	Macrofuels deliverable 6.2
Process biogas (26% methane)	kg	20.2 (5.25)	155 (40.3)	Macrofuels deliverable 6.2
Export biogas (26% methane)	kg	14.0 (3.64)	108(28.1)	Macrofuels deliverable 6.2
Digestate (N 0.32%) (P 0.09%) (K 0.09%)	kg	432	3325	Macrofuels deliverable 6.2
Waste water - Filtration	kg	1809	13914	Macrofuels deliverable 6.2
Waste water - Purification	kg	18.4	142	Macrofuels deliverable 6.2
Waste water - AD	kg	244	1873	Macrofuels deliverable 6.2
Flue gas	m3	121	933	Macrofuels deliverable 6.2
Storage vent emissions	kg	0.031	0.24	Macrofuels deliverable 6.2
Fermentation vent emissions	kg	19.7	152	Macrofuels deliverable 6.2

Table B - 8 Inventory data for the furanics scenario with furanics and bio-butanol blend

Flow Name	unit	Amount per tonne of wet seaweed	Amount per tonne of dry seaweed	Source
Inputs				
Hydrochloric acid	kg	18.3	141	Macrofuels deliverable 6.2
Toluene	kg	1.06	8.18	Macrofuels deliverable 6.2
Butanol	kg	174	1338	Macrofuels deliverable 6.2
Hydrogen	kg	1.18	9.07	Macrofuels deliverable 6.2
Sodium hydroxide	kg	16.2	125	Macrofuels deliverable 6.2
Air	dm ³	72.7	559	Macrofuels deliverable 6.2
Electricity	kWh	2.44	18.8	Macrofuels deliverable 6.2
Outputs				
Bio-Furanics	kg	193	1488	Macrofuels deliverable 6.2
Total Biogas production (33% methane)	kg	11.3 (3.76)	86.6 (28.9)	Macrofuels deliverable 6.2
Process biogas (33% methane)	kg	11.3 (3.76)	86.6 (28.9)	Macrofuels deliverable 6.2
Export biogas (33% methane)	kg	0	0	Macrofuels deliverable 6.2
Digestate (N 0.55%) (P 0%) (K 0.59%)	kg	436	3353	Macrofuels deliverable 6.2
Waste water - Filtration	kg	0.624	4.80	Macrofuels deliverable 6.2
Waste water - Purification	kg	2.05	15.8	Macrofuels deliverable 6.2
Waste water - AD	kg	567.37	4364	Macrofuels deliverable 6.2
Flue gas	m ³	84.0	646	Macrofuels deliverable 6.2
Storage vent emissions	kg	0.0095	0.073	Macrofuels deliverable 6.2

Table B - 9 Inventory data for the furanics scenario: furanics fuel additive only

Flow Name	unit	Amount per tonne of wet seaweed	Amount per tonne of dry seaweed	Source
Inputs				
Hydrochloric acid	kg	18.3	141	Macrofuels deliverable 6.2
Toluene	kg	1.06	8.18	Macrofuels deliverable 6.2
Bio-Butanol from ABE process	kg	2.27	17.5	Macrofuels deliverable 6.2
Hydrogen	kg	1.18	9.07	Macrofuels deliverable 6.2
Sodium hydroxide	kg	16.2	125	Macrofuels deliverable 6.2
Air	dm ³	72.7	559	Macrofuels deliverable 6.2
Electricity	kWh	2.44	18.8	Macrofuels deliverable 6.2
Outputs				
Bio-Furanics	kg	21.9	168	Macrofuels deliverable 6.2
Total Biogas production (33% methane)	kg	11.3 (3.76)	86.6 (28.9)	Macrofuels deliverable 6.2
Process biogas (33% methane)	kg	11.3 (3.76)	86.6 (28.9)	Macrofuels deliverable 6.2
Export biogas (33% methane)	kg	0	0	Macrofuels deliverable 6.2
Digestate (N 0.55%) (P 0%) (K 0.59%)	kg	436	3353	Macrofuels deliverable 6.2
Waste water - Filtration	kg	0.624	4.80	Macrofuels deliverable 6.2
Waste water - Purification	kg	2.05	15.8	Macrofuels deliverable 6.2
Waste water - AD	kg	567	4364	Macrofuels deliverable 6.2
Flue gas	m ³	84.0	646	Macrofuels deliverable 6.2
Storage vent emissions	kg	0.0095	0.073	Macrofuels deliverable 6.2

Table B - 10 Fermentation and storage vent emissions inventory table

Waste stream	Emissions to air	Percentage by mass (%)
Fermentation vent emissions (EtOH)	Ethanol	1.4%
	CO2 biogenic	93%
	Oxygen	3.2%
	Water	2.6%
Fermentation vent emissions (ABE)	Ethanol	0.1%
	CO2 biogenic	92%
	Oxygen	3.4%
	Water	4.6%
Storage vent emissions (EtOH)	CO2 biogenic	37%
	Hydrogen	54%
	Water	8.9%
Storage vent emissions (ABE)	CO2 biogenic	37%
	Hydrogen	54%
	Water	9%
Storage vent emissions (Furanics)	Nitrogen	100%

Table B - 11 Flue gas emissions to air for ethanol, ABE and furanics scenarios

Waste stream	Amount (m3)	Emissions to air	Amount (kg)
Flue gas AD (EtOH)	172577	Oxygen	3125
		Nitrogen, atmospheric	101844
		CO2, biogenic	37026
		Sulfuric acid	64
		Hydrogen	0.02
		Hydrogen sulfide	0.0002
Flue gas AD (ABE)	139985	Oxygen	2728
		Nitrogen, atmospheric	88803
		CO2, biogenic	32845
		Sulfuric acid	69
		Hydrogen	0.02
		Hydrogen sulfide	0.0002
Flue gas AD (Furanics)	88440	Oxygen	1789.2
		Nitrogen, atmospheric	58236.3
		CO2, biogenic	18444
		Water	9970.5

Table B - 12 Inventory table of use emissions associated with each scenario

Flow Name	unit	Amount per tonne of wet seaweed	Amount per MJ of fuel produced	Source
Ethanol				
VOC, volatile organic compounds	kg	6.37E-03	2.97E-05	REET database
Carbon monoxide, biogenic	kg	1.29E-01	6.00E-04	REET database
Nitrogen oxides	kg	5.68E-03	2.65E-05	REET database
Particulates < 10 um	kg	2.55E-04	1.19E-06	REET database
Particulates < 2.5 um	kg	2.25E-04	1.05E-06	REET database
Methane	kg	4.08E-04	1.90E-06	REET database
Carbon dioxide, biogenic	kg	1.26E+01	5.88E-02	REET database
nitrogen dioxide	kg	3.61E-04	1.68E-06	REET database
Butanol				
VOC, volatile organic compounds	kg	7.98E-03	2.97E-05	REET database
Carbon monoxide, biogenic	kg	1.61E-01	6.00E-04	REET database
Nitrogen oxides	kg	7.11E-03	2.65E-05	REET database
Methane	kg	5.11E-04	1.90E-06	REET database
Carbon dioxide, biogenic	kg	1.58E+01	6.82E-02	REET database
Particulates, < 10 um	kg	3.20E-04	1.19E-06	REET database
Particulates, < 2.5 um	kg	2.82E-04	1.05E-06	REET database
Nitrogen dioxide	kg	4.52E-04	1.68E-06	REET database
Furanics (assumed to be the same as butanol)				
VOC, volatile organic compounds	kg	1.89E-01	2.97E-05	REET database
Carbon monoxide, biogenic	kg	3.83E+00	6.00E-04	REET database
Nitrogen oxides	kg	1.69E-01	2.65E-05	REET database
Particulates, < 10 um	kg	7.60E-03	1.19E-06	REET database
Particulates, < 2.5 um	kg	6.70E-03	1.05E-06	REET database
Methane	kg	1.21E-02	1.90E-06	REET database
Carbon dioxide, biogenic	kg	4.35E+02	6.82E-02	REET database
Nitrous oxide	kg	1.07E-02	1.68E-06	REET database

Table B - 13 Inventory table of secondary data for materials used in processing including transport of raw materials and distribution of biofuels

Input	Process name	Database	Geography	Reference year	Valid until
Hydrochloric acid	Hydrochloric acid, without water, in 30% solution state {RER} market for APOS, U	Ecoinvent 3.4	Europe	1998	2017
Toluene	Toluene, liquid {RER} production APOS, U	Ecoinvent 3.4	Europe	2001	2017
Hydrogen	Hydrogen, liquid {RER} market for APOS, U	Ecoinvent 3.4	Europe	2011	2017
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {RER} chlor-alkali electrolysis, diaphragm cell (14%); Sodium hydroxide, without water, in 50% solution state {RER} chlor-alkali electrolysis, membrane cell (40%); Sodium hydroxide, without water, in 50% solution state {RER} chlor-alkali electrolysis, mercury cell (46%);	Ecoinvent 3.4	Europe	2000	2017
Air	Compressed air, 1000 kPa gauge {RER} compressed air production, 1000 kPa gauge, <30kW, average generation APOS, U	Ecoinvent 3.4	Europe	2010	2017
Electricity	Electricity, medium voltage {Europe without Switzerland} market group for APOS, U	Ecoinvent 3.4	Europe without Switzerland	2015	2017
Water	Water, deionised, from tap water, at user {Europe without Switzerland} market for water, deionised, from tap water, at user APOS, U	Ecoinvent 3.4	Europe without Switzerland	2011	2017
Enzymes	Enzymes {RER} enzymes production APOS, U	Ecoinvent 3.4	Europe	2015	2020
Road freight, lorry	Transport, freight, lorry, unspecified {GLO} market for APOS, U	Ecoinvent 3.4	Global	2012	2017
Rail freight	Transport, freight train {Europe without Switzerland} market for APOS, U	Ecoinvent 3.4	Europe without Switzerland	2011	2017

Sea freight, transoceanic ship	Transport, freight, sea, transoceanic ship {GLO} market for APOS, U	Ecoinvent 3.4	Global	2011	2017
Transport barge	Transport, freight, inland waterways, barge {RER} processing APOS, U	Ecoinvent 3.4	Europe	2000	2017
Biofuel distribution	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO} market for APOS, U	Ecoinvent 3.4	Global	2011	2017

Table B - 14 Secondary data for credit for digestate as substitution for inorganic fertilisers

Input	Process name	Database
Nitrogen benefit	Ammonium nitrate, as N {RER} ammonium nitrate production APOS, U	Ecoinvent 3.4
Phosphorous benefit	Phosphate fertiliser, as P ₂ O ₅ {RER} single superphosphate production APOS, U	Ecoinvent 3.4
Potassium benefit	Potassium chloride, as K ₂ O {RER} citric acid production APOS, U	Ecoinvent 3.4

Table B - 15 Secondary data for growing equipment materials including recycled content and manufacturing processes

Input	Process name (Baseline)	Process name (100% recycled content)	Notes	Database	Geography	Reference year	Valid until
Materials							
AlgaeNet - 30cm mesh	Polyethylene terephthalate (PET) granulate, production mix, at plant, amorphous RER	Polyethylene terephthalate, granulate, amorphous, recycled {Europe without Switzerland} polyethylene terephthalate production, granulate, amorphous, recycled APOS, U	Net made from Polyester (PET) via extrusion (film). Transported by road freight and sea freight	ELCD	Europe	1999	2010
Buoys	Polyethylene high density granulate (PE-HD), production mix, at plant RER	Polyethylene, high density, granulate, recycled {Europe without Switzerland} polyethylene production, high density, granulate, recycled APOS, U	Shell made from Polyethylene (HDPE). Made via blow moulding. Transported by road freight and sea freight	ELCD	Europe	1999	2009
	Polystyrene, expandable {RER} production APOS, U		Foam fill made from polystyrene. Assumed Polystyrene density of 25 kg/m3. Made via blow moulding. Transported by road freight and sea freight	Ecoinvent 3.4	Europe	2001	2017
Dampening block	Concrete, normal {CH} unreinforced concrete production, with cement CEM II/A APOS, U		Block made of concrete. Transported by road freight and sea freight	Ecoinvent 3.4	Switzerland		
Hook - 100mm	Steel hot dip galvanized (ILCD), blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S	Steel hot dip galvanized, including recycling, blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S	Hook made from galvanised steel. Transported by road freight and sea freight	ELCD	Global	2007	2015

Anchor	Steel hot dip galvanized (ILCD), blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S	Steel hot dip galvanized, including recycling, blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S	Anchor made from galvanised steel. Transported by road freight and sea freight	ELCD	Global	2007	2015
Chain - 10mm	Steel hot dip galvanized (ILCD), blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S	Steel hot dip galvanized, including recycling, blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S	Chain made from galvanised steel. Transported by road freight and sea freight	ELCD	Global	2007	2015
PE pipe - 110mm	Polyethylene high density granulate (PE-HD), production mix, at plant RER	Polyethylene, high density, granulate, recycled {Europe without Switzerland} polyethylene production, high density, granulate, recycled APOS, U	Pipe made from Polyethylene via extrusion (pipe). Transported by road freight and sea freight	ELCD	Europe	1999	2009
Processes							
Extrusion, plastic film	Extrusion, plastic film {RER} production APOS, U			Ecoinvent 3.4	Europe	1993	2017
Blow moulding	Blow moulding {RER} production APOS, U			Ecoinvent 3.4	Europe	1993	2017
Extrusion, plastic pipe	Extrusion, plastic pipes {RER} production APOS, U			Ecoinvent 3.4	Europe	1993	2017

Table B - 16 Carbon sequestration in the deep sea inventory table

Input	Amount	Unit	Source
Dry weight % of seaweed	13	%	Macrofuels deliverable 6.2
Carbon content of dry seaweed	35	%	Macrofuels deliverable 6.2
Loss of seaweed during growing (DW)	26	%	Nielsen et al, June 2014, Growth dynamics of <i>Saccharina latissima</i> (Laminariales, Phaeophyceae) in Aarhus Bay, Denmark, and along the species' distribution range.
Carbon sequestered in deep sea (as Dissolved organic carbon (DOC) and particulate organic carbon (POC))	12.8	%	D.Krause-Jensen, Nature Geoscience, September 2016, Substantial role of macroalgae in marine carbon sequestration.
Calculation CO₂-sequestration per tonne seaweed(ww)			
Amount seaweed lost to sea	46	kg C	
Carbon from seaweed lost to sea	16	kg C	
Carbon from seaweed sequestered in deep sea	2.0	kg C	
CO ₂ sequestered	7.5	kg CO ₂	

Table B - 17 At sea storage bags inventory table

Component	Process name	Amount	Unit	Notes
Materials				
Storage bag	Polyethylene terephthalate (PET) granulate, production mix, at plant, amorphous RER	75	kg	25 m3 volume holds 7500 kg of wet seaweed
Processing				
Extrusion	Extrusion, co-extrusion {RoW} of plastic sheets APOS, U			

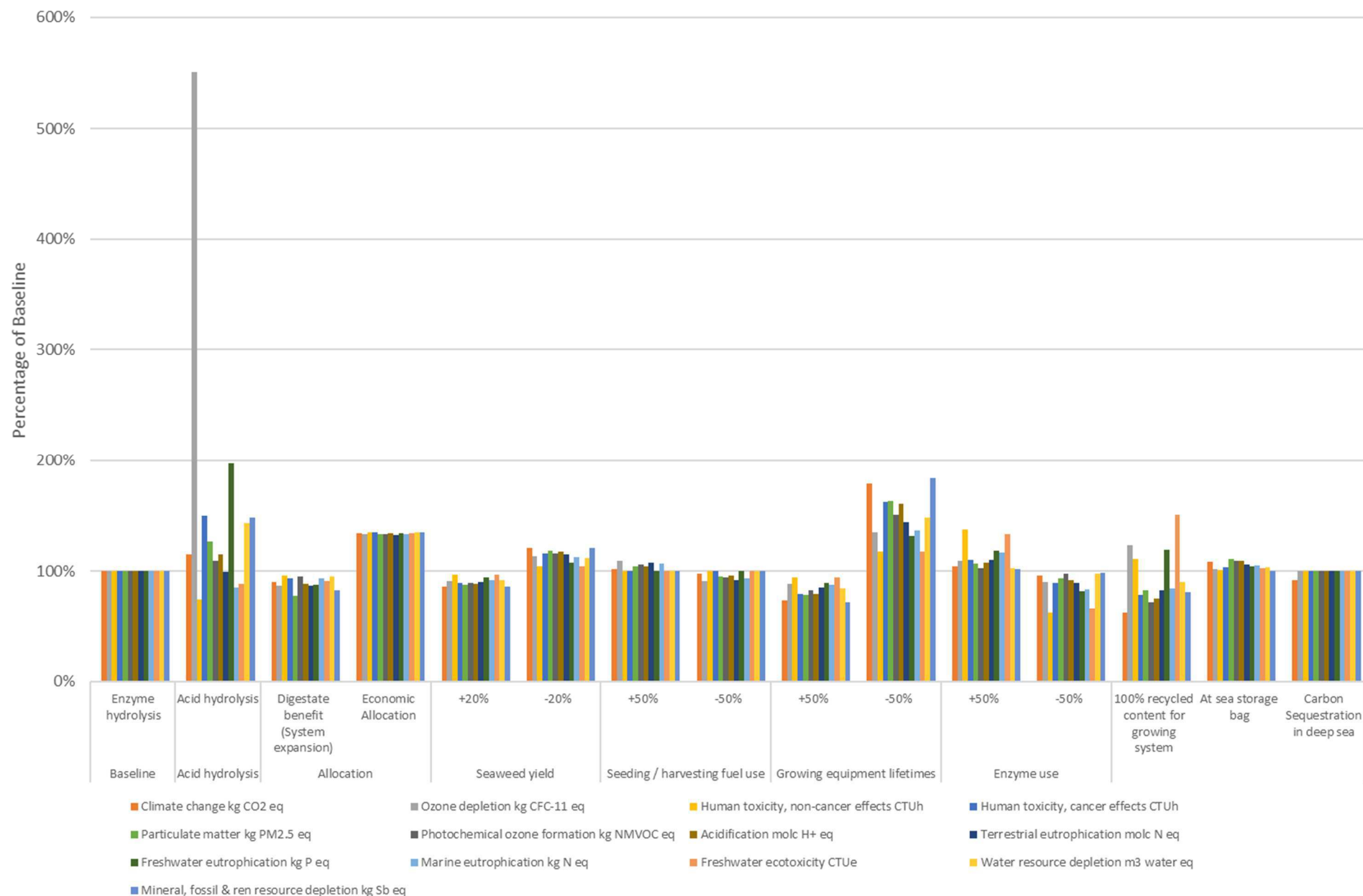


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Annex C: *Sensitivity analysis result*

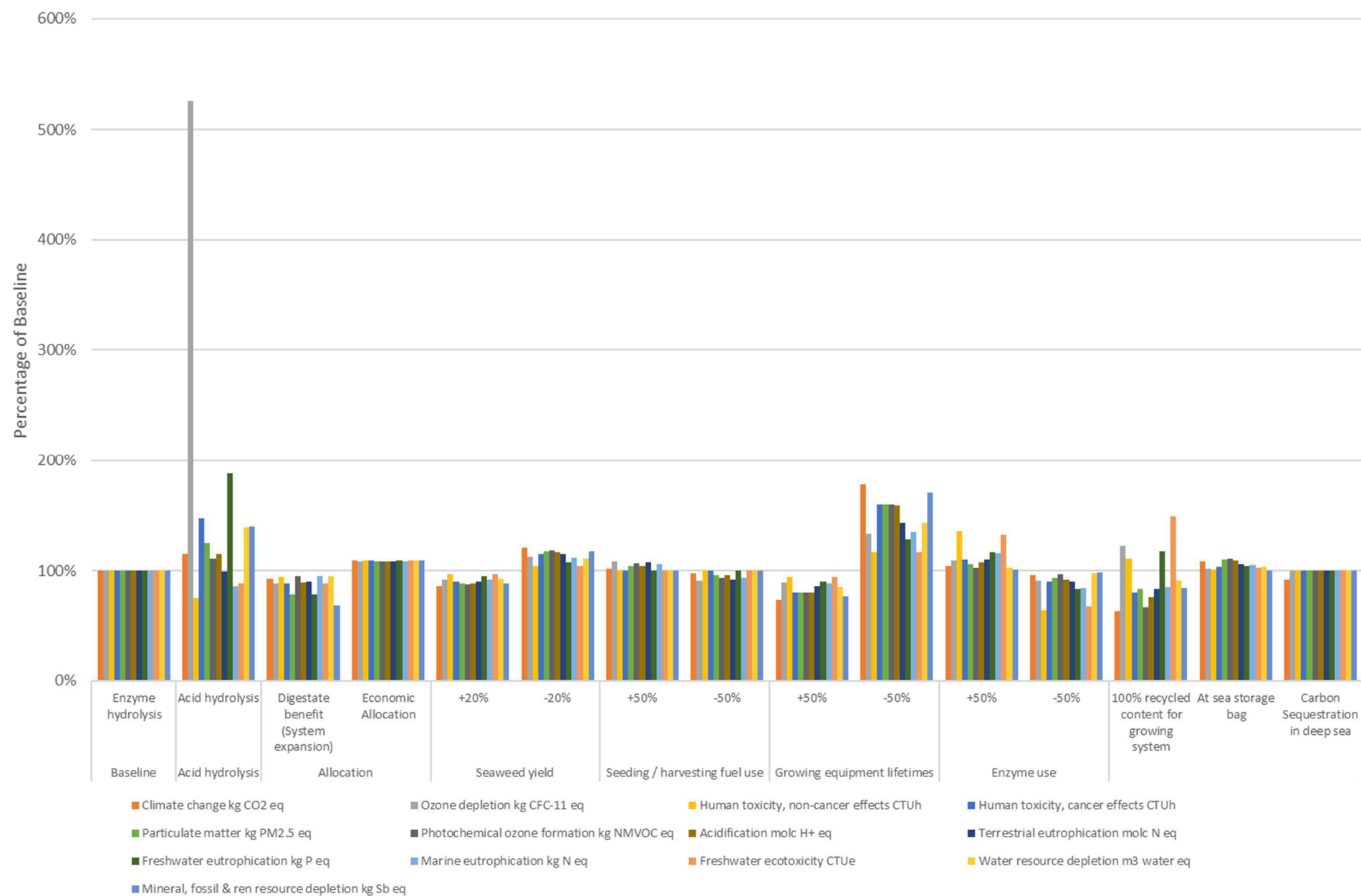
1 Ethanol from ethanol fermentation (EtOH process)

		Baseline	Acid hydrolysis	Allocation			Seaweed yield		Seeding / harvesting fuel use		Growing equipment lifetimes		Enzyme use		100% recycled content for growing system	At sea storage bag	Carbon Sequestration in deep sea
Impact category	Unit	Enzyme hydrolysis	Acid hydrolysis	Digestate benefit (System expansion)	Acetate (System expansion)	Economic Allocation	+20%	-20%	+50%	-50%	+50%	-50%	+50%	-50%			
Climate change	kg CO ₂ eq	1.81E-01	2.09E-01	1.64E-01	1.81E-01	2.44E-01	1.56E-01	2.19E-01	1.85E-01	1.77E-01	1.33E-01	3.25E-01	1.89E-01	1.74E-01	1.12E-01	1.96E-01	1.66E-01
Ozone depletion	kg CFC-11 eq	7.86E-09	4.33E-08	6.81E-09	7.86E-09	1.05E-08	7.16E-09	8.91E-09	8.57E-09	7.15E-09	6.94E-09	1.06E-08	8.61E-09	7.11E-09	9.71E-09	8.01E-09	7.86E-09
Human toxicity, non-cancer effects	CTUh	5.25E-08	3.91E-08	5.04E-08	5.25E-08	7.07E-08	5.09E-08	5.48E-08	5.25E-08	5.24E-08	4.94E-08	6.16E-08	7.23E-08	3.26E-08	5.84E-08	5.29E-08	5.25E-08
Human toxicity, cancer effects	CTUh	3.88E-09	5.80E-09	3.62E-09	3.88E-09	5.22E-09	3.47E-09	4.49E-09	3.88E-09	3.87E-09	3.07E-09	6.30E-09	4.28E-09	3.47E-09	3.06E-09	4.02E-09	3.88E-09
Particulate matter	kg PM _{2.5} eq	5.81E-05	7.34E-05	4.51E-05	5.81E-05	7.75E-05	5.10E-05	6.87E-05	6.07E-05	5.54E-05	4.59E-05	9.47E-05	6.18E-05	5.43E-05	4.81E-05	6.44E-05	5.81E-05
Photochemical ozone formation	kg NMVOC eq	8.11E-04	8.86E-04	7.75E-04	8.11E-04	1.08E-03	7.26E-04	9.40E-04	8.57E-04	7.65E-04	6.73E-04	1.23E-03	8.31E-04	7.92E-04	5.85E-04	8.88E-04	8.11E-04
Acidification	molc H ⁺ eq	8.84E-04	1.02E-03	7.80E-04	8.84E-04	1.18E-03	7.81E-04	1.04E-03	9.22E-04	8.46E-04	7.05E-04	1.42E-03	9.55E-04	8.13E-04	6.69E-04	9.70E-04	8.84E-04
Terrestrial eutrophication	molc N eq	2.27E-03	2.26E-03	1.96E-03	2.27E-03	3.01E-03	2.03E-03	2.61E-03	2.45E-03	2.08E-03	1.93E-03	3.26E-03	2.50E-03	2.03E-03	1.88E-03	2.41E-03	2.27E-03
Freshwater eutrophication	kg P eq	2.40E-05	4.74E-05	2.10E-05	2.40E-05	3.23E-05	2.28E-05	2.60E-05	2.41E-05	2.40E-05	2.15E-05	3.16E-05	2.84E-05	1.97E-05	2.87E-05	2.51E-05	2.40E-05
Marine eutrophication	kg N eq	2.55E-04	2.18E-04	2.40E-04	2.55E-04	3.40E-04	2.34E-04	2.88E-04	2.72E-04	2.39E-04	2.24E-04	3.49E-04	2.98E-04	2.13E-04	2.15E-04	2.69E-04	2.55E-04
Freshwater ecotoxicity	CTUe	4.99E-01	4.40E-01	4.56E-01	4.99E-01	6.71E-01	4.84E-01	5.22E-01	5.00E-01	4.99E-01	4.70E-01	5.87E-01	6.67E-01	3.31E-01	7.55E-01	5.14E-01	4.99E-01
Water resource depletion	m ³ water eq	8.81E-04	1.26E-03	8.42E-04	8.81E-04	1.19E-03	8.11E-04	9.88E-04	8.82E-04	8.81E-04	7.41E-04	1.30E-03	9.04E-04	8.59E-04	7.95E-04	9.13E-04	8.81E-04
Mineral, fossil & ren resource depletion	kg Sb eq	8.17E-06	1.21E-05	6.75E-06	8.17E-06	1.10E-05	7.03E-06	9.89E-06	8.17E-06	8.17E-06	5.89E-06	1.50E-05	8.31E-06	8.04E-06	6.62E-06	8.19E-06	8.17E-06



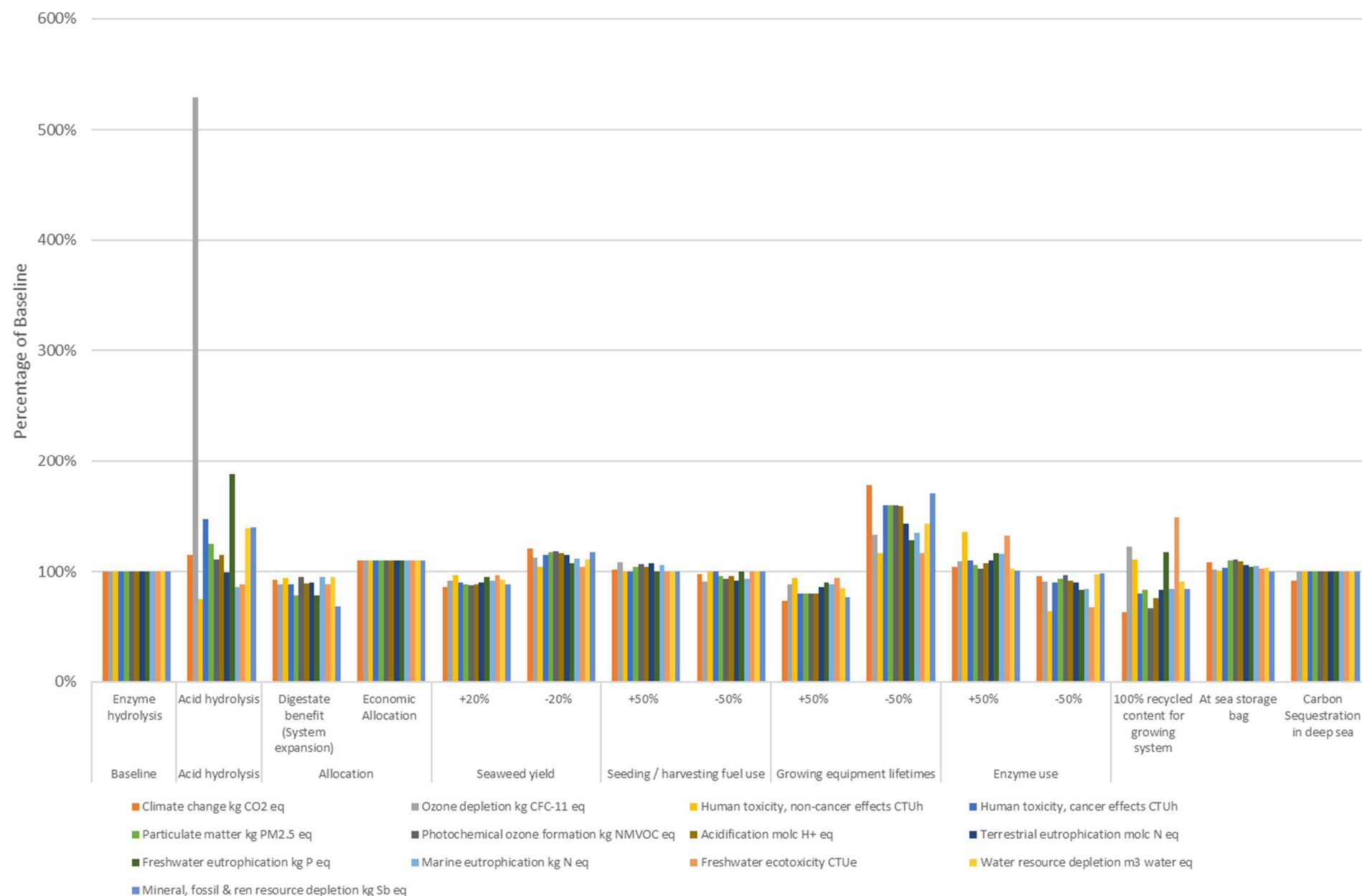
2 Ethanol from ABE process

Impact category	Unit	Baseline	Acid hydrolysis	Allocation			Seaweed yield		Seeding / harvesting fuel use		Growing equipment lifetimes		Enzyme use		100% recycled content for growing system	At sea storage bag	Carbon Sequestration in deep sea
		Enzyme hydrolysis	Acid hydrolysis	Digestate benefit (System expansion)	Acetate (System expansion)	Economic Allocation	+20%	-20%	+50%	-50%	+50%	-50%	+50%	-50%			
Climate change	kg CO ₂ eq	1.69E-01	1.95E-01	1.57E-01	1.88E-01	1.84E-01	1.45E-01	2.04E-01	1.73E-01	1.66E-01	1.25E-01	3.01E-01	1.76E-01	1.62E-01	1.06E-01	1.83E-01	1.55E-01
Ozone depletion	kg CFC-11 eq	7.67E-09	4.04E-08	6.81E-09	9.18E-09	8.34E-09	7.02E-09	8.64E-09	8.33E-09	7.01E-09	6.82E-09	1.02E-08	8.36E-09	6.98E-09	9.38E-09	7.80E-09	7.67E-09
Human toxicity, non-cancer effects	CTUh	5.05E-08	3.81E-08	4.76E-08	6.06E-08	5.50E-08	4.90E-08	5.26E-08	5.05E-08	5.04E-08	4.76E-08	5.89E-08	6.87E-08	3.22E-08	5.59E-08	5.09E-08	5.05E-08
Human toxicity, cancer effects	CTUh	3.75E-09	5.53E-09	3.32E-09	4.19E-09	4.09E-09	3.37E-09	4.32E-09	3.75E-09	3.75E-09	3.01E-09	5.99E-09	4.12E-09	3.38E-09	2.99E-09	3.88E-09	3.75E-09
Particulate matter	kg PM _{2.5} eq	5.66E-05	7.07E-05	4.44E-05	6.09E-05	6.15E-05	5.01E-05	6.64E-05	5.90E-05	5.41E-05	4.53E-05	9.03E-05	6.01E-05	5.31E-05	4.74E-05	6.25E-05	5.66E-05
Photochemical ozone formation	kg NMVOC eq	6.39E-04	7.08E-04	6.10E-04	7.01E-04	6.94E-04	5.61E-04	7.58E-04	6.82E-04	5.97E-04	5.12E-04	1.02E-03	6.57E-04	6.22E-04	4.31E-04	7.10E-04	6.39E-04
Acidification	molc H ⁺ eq	8.41E-04	9.67E-04	7.51E-04	9.22E-04	9.15E-04	7.45E-04	9.84E-04	8.76E-04	8.06E-04	6.76E-04	1.34E-03	9.06E-04	7.75E-04	6.43E-04	9.20E-04	8.41E-04
Terrestrial eutrophication	molc N eq	2.13E-03	2.12E-03	1.92E-03	2.40E-03	2.31E-03	1.92E-03	2.45E-03	2.29E-03	1.96E-03	1.82E-03	3.04E-03	2.34E-03	1.91E-03	1.77E-03	2.26E-03	2.13E-03
Freshwater eutrophication	kg P eq	2.43E-05	4.59E-05	1.91E-05	2.82E-05	2.65E-05	2.31E-05	2.61E-05	2.44E-05	2.43E-05	2.20E-05	3.13E-05	2.83E-05	2.03E-05	2.86E-05	2.53E-05	2.43E-05
Marine eutrophication	kg N eq	2.45E-04	2.11E-04	2.33E-04	2.81E-04	2.66E-04	2.25E-04	2.75E-04	2.60E-04	2.30E-04	2.16E-04	3.31E-04	2.84E-04	2.06E-04	2.08E-04	2.58E-04	2.45E-04
Freshwater ecotoxicity	CTUe	4.81E-01	4.27E-01	4.27E-01	5.60E-01	5.24E-01	4.67E-01	5.02E-01	4.82E-01	4.80E-01	4.54E-01	5.62E-01	6.36E-01	3.26E-01	7.16E-01	4.94E-01	4.81E-01
Water resource depletion	m ³ water eq	9.02E-04	1.25E-03	8.58E-04	1.05E-03	9.84E-04	8.36E-04	9.99E-04	9.02E-04	9.01E-04	7.72E-04	1.29E-03	9.22E-04	8.81E-04	8.22E-04	9.31E-04	9.02E-04
Mineral, fossil & ren resource depletion	kg Sb eq	8.98E-06	1.26E-05	6.17E-06	1.08E-05	9.80E-06	7.92E-06	1.06E-05	8.98E-06	8.98E-06	6.87E-06	1.53E-05	9.10E-06	8.85E-06	7.54E-06	8.99E-06	8.98E-06



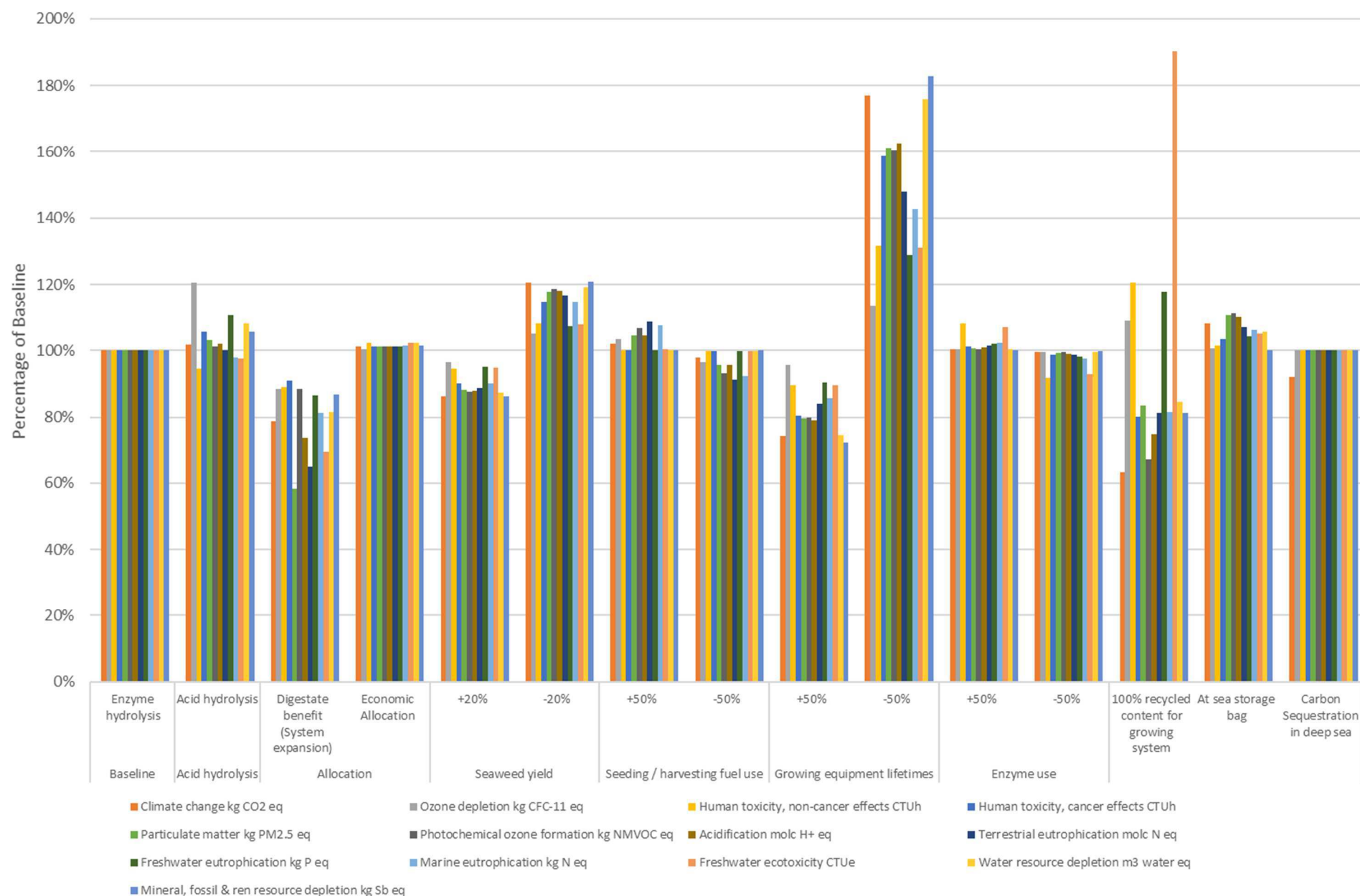
3 Butanol from ABE process

		Baseline	Acid hydrolysis	Allocation			Seaweed yield		Seeding / harvesting fuel use		Growing equipment lifetimes		Enzyme use		100% recycled content for growing system	At sea storage bag	Carbon Sequestration in deep sea
Impact category	Unit	Enzyme hydrolysis	Acid hydrolysis	Digestate benefit (System expansion)	Acetate (System expansion)	Economic Allocation	+20%	-20%	+50%	-50%	+50%	-50%	+50%	-50%			
Climate change	kg CO2 eq	1.69E-01	1.95E-01	1.57E-01	1.88E-01	1.84E-01	1.45E-01	2.04E-01	1.73E-01	1.66E-01	1.25E-01	3.01E-01	1.76E-01	1.62E-01	1.06E-01	1.83E-01	1.55E-01
Ozone depletion	kg CFC-11 eq	7.67E-09	4.04E-08	6.81E-09	9.18E-09	8.34E-09	7.02E-09	8.64E-09	8.33E-09	7.01E-09	6.82E-09	1.02E-08	8.36E-09	6.98E-09	9.38E-09	7.80E-09	7.67E-09
Human toxicity, non-cancer effects	CTUh	5.05E-08	3.81E-08	4.76E-08	6.06E-08	5.50E-08	4.90E-08	5.26E-08	5.05E-08	5.04E-08	4.76E-08	5.89E-08	6.87E-08	3.22E-08	5.59E-08	5.09E-08	5.05E-08
Human toxicity, cancer effects	CTUh	3.75E-09	5.53E-09	3.32E-09	4.19E-09	4.09E-09	3.37E-09	4.32E-09	3.75E-09	3.75E-09	3.01E-09	5.99E-09	4.12E-09	3.38E-09	2.99E-09	3.88E-09	3.75E-09
Particulate matter	kg PM2.5 eq	5.66E-05	7.07E-05	4.44E-05	6.09E-05	6.15E-05	5.01E-05	6.64E-05	5.90E-05	5.41E-05	4.53E-05	9.03E-05	6.01E-05	5.31E-05	4.74E-05	6.25E-05	5.66E-05
Photochemical ozone formation	kg NMVOC eq	6.39E-04	7.08E-04	6.10E-04	7.01E-04	6.94E-04	5.61E-04	7.58E-04	6.82E-04	5.97E-04	5.12E-04	1.02E-03	6.57E-04	6.22E-04	4.31E-04	7.10E-04	6.39E-04
Acidification	molc H+ eq	8.41E-04	9.67E-04	7.51E-04	9.22E-04	9.15E-04	7.45E-04	9.84E-04	8.76E-04	8.06E-04	6.76E-04	1.34E-03	9.06E-04	7.75E-04	6.43E-04	9.20E-04	8.41E-04
Terrestrial eutrophication	molc N eq	2.13E-03	2.12E-03	1.92E-03	2.40E-03	2.31E-03	1.92E-03	2.45E-03	2.29E-03	1.96E-03	1.82E-03	3.04E-03	2.34E-03	1.91E-03	1.77E-03	2.26E-03	2.13E-03
Freshwater eutrophication	kg P eq	2.43E-05	4.59E-05	1.91E-05	2.82E-05	2.65E-05	2.31E-05	2.61E-05	2.44E-05	2.43E-05	2.20E-05	3.13E-05	2.83E-05	2.03E-05	2.86E-05	2.53E-05	2.43E-05
Marine eutrophication	kg N eq	2.45E-04	2.11E-04	2.33E-04	2.81E-04	2.66E-04	2.25E-04	2.75E-04	2.60E-04	2.30E-04	2.16E-04	3.31E-04	2.84E-04	2.06E-04	2.08E-04	2.58E-04	2.45E-04
Freshwater ecotoxicity	CTUe	4.81E-01	4.27E-01	4.27E-01	5.60E-01	5.24E-01	4.67E-01	5.02E-01	4.82E-01	4.80E-01	4.54E-01	5.62E-01	6.36E-01	3.26E-01	7.16E-01	4.94E-01	4.81E-01
Water resource depletion	m3 water eq	9.02E-04	1.25E-03	8.58E-04	1.05E-03	9.84E-04	8.36E-04	9.99E-04	9.02E-04	9.01E-04	7.72E-04	1.29E-03	9.22E-04	8.81E-04	8.22E-04	9.31E-04	9.02E-04
Mineral, fossil & ren resource depletion	kg Sb eq	8.98E-06	1.26E-05	6.17E-06	1.08E-05	9.80E-06	7.92E-06	1.06E-05	8.98E-06	8.98E-06	6.87E-06	1.53E-05	9.10E-06	8.85E-06	7.54E-06	8.99E-06	8.98E-06



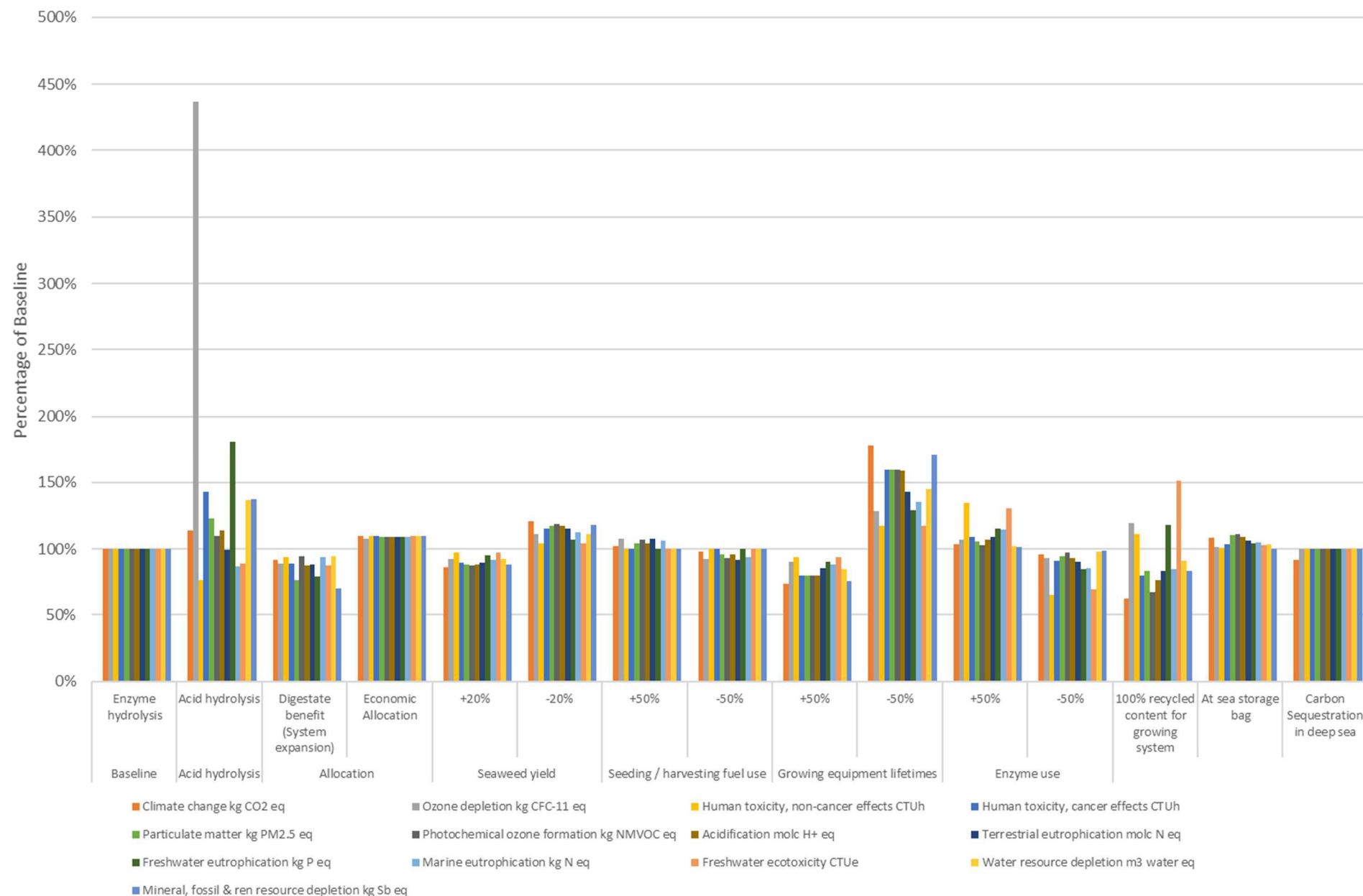
4 Furanic Fuel additive

Impact category	Unit	Baseline	Acid hydrolysis	Allocation			Seaweed yield		Seeding / harvesting fuel use		Growing equipment lifetimes		Enzyme use		100% recycled content for growing system	At sea storage bag	Carbon Sequestration in deep sea
		Enzyme hydrolysis	Acid hydrolysis	Digestate benefit (System expansion)	Acetate (System expansion)	Economic Allocation	+20%	-20%	+50%	-50%	+50%	-50%	+50%	-50%			
Climate change	kg CO ₂ eq	1.57E-01	1.59E-01	1.23E-01	1.59E-01	1.59E-01	1.35E-01	1.89E-01	1.60E-01	1.53E-01	1.16E-01	2.77E-01	1.57E-01	1.56E-01	9.91E-02	1.69E-01	1.44E-01
Ozone depletion	kg CFC-11 eq	1.74E-08	2.09E-08	1.54E-08	1.75E-08	1.74E-08	1.68E-08	1.82E-08	1.80E-08	1.68E-08	1.66E-08	1.97E-08	1.74E-08	1.73E-08	1.89E-08	1.75E-08	1.74E-08
Human toxicity, non-cancer effects	CTUh	2.44E-08	2.31E-08	2.18E-08	2.56E-08	2.50E-08	2.31E-08	2.64E-08	2.45E-08	2.44E-08	2.19E-08	3.21E-08	2.64E-08	2.24E-08	2.94E-08	2.48E-08	2.44E-08
Human toxicity, cancer effects	CTUh	3.46E-09	3.66E-09	3.15E-09	3.51E-09	3.50E-09	3.12E-09	3.98E-09	3.47E-09	3.46E-09	2.78E-09	5.50E-09	3.50E-09	3.42E-09	2.77E-09	3.58E-09	3.46E-09
Particulate matter	kg PM _{2.5} eq	5.02E-05	5.17E-05	2.93E-05	5.07E-05	5.08E-05	4.43E-05	5.91E-05	5.24E-05	4.80E-05	4.00E-05	8.09E-05	5.06E-05	4.98E-05	4.19E-05	5.55E-05	5.02E-05
Photochemical ozone formation	kg NMVOC eq	5.76E-04	5.84E-04	5.10E-04	5.83E-04	5.83E-04	5.05E-04	6.84E-04	6.15E-04	5.38E-04	4.60E-04	9.24E-04	5.78E-04	5.74E-04	3.86E-04	6.41E-04	5.76E-04
Acidification	molc H ⁺ eq	7.20E-04	7.34E-04	5.33E-04	7.29E-04	7.30E-04	6.34E-04	8.51E-04	7.52E-04	6.89E-04	5.70E-04	1.17E-03	7.28E-04	7.13E-04	5.40E-04	7.92E-04	7.20E-04
Terrestrial eutrophication	molc N eq	1.73E-03	1.73E-03	1.12E-03	1.76E-03	1.75E-03	1.54E-03	2.02E-03	1.88E-03	1.58E-03	1.45E-03	2.56E-03	1.75E-03	1.70E-03	1.41E-03	1.85E-03	1.73E-03
Freshwater eutrophication	kg P eq	2.20E-05	2.44E-05	1.90E-05	2.25E-05	2.23E-05	2.10E-05	2.37E-05	2.21E-05	2.20E-05	1.99E-05	2.84E-05	2.25E-05	2.16E-05	2.60E-05	2.30E-05	2.20E-05
Marine eutrophication	kg N eq	1.84E-04	1.80E-04	1.49E-04	1.87E-04	1.86E-04	1.66E-04	2.10E-04	1.97E-04	1.70E-04	1.57E-04	2.62E-04	1.88E-04	1.79E-04	1.50E-04	1.95E-04	1.84E-04
Freshwater ecotoxicity	CTUe	2.37E-01	2.32E-01	1.65E-01	2.46E-01	2.43E-01	2.25E-01	2.56E-01	2.38E-01	2.37E-01	2.13E-01	3.11E-01	2.54E-01	2.21E-01	4.52E-01	2.50E-01	2.37E-01
Water resource depletion	m ³ water eq	4.66E-04	5.04E-04	3.80E-04	4.83E-04	4.76E-04	4.07E-04	5.55E-04	4.67E-04	4.66E-04	3.48E-04	8.20E-04	4.68E-04	4.64E-04	3.94E-04	4.93E-04	4.66E-04
Mineral, fossil & ren resource depletion	kg Sb eq	6.93E-06	7.32E-06	6.01E-06	7.13E-06	7.03E-06	5.97E-06	8.37E-06	6.93E-06	6.93E-06	5.01E-06	1.27E-05	6.94E-06	6.91E-06	5.62E-06	6.94E-06	6.93E-06



5 Furanic fuel/butanol Blend

		Baseline	Acid hydrolysis	Allocation			Seaweed yield		Seeding / harvesting fuel use		Growing equipment lifetimes		Enzyme use		100% recycled content for growing system	At sea storage bag	Carbon Sequestration in deep sea
Impact category	Unit	Enzyme hydrolysis	Acid hydrolysis	Digestate benefit (System expansion)	Acetate (System expansion)	Economic Allocation	+20%	-20%	+50%	-50%	+50%	-50%	+50%	-50%			
Climate change	kg CO ₂ eq	1.68E-01	1.91E-01	1.54E-01	1.85E-01	1.84E-01	1.45E-01	2.03E-01	1.71E-01	1.64E-01	1.24E-01	2.99E-01	1.74E-01	1.62E-01	1.05E-01	1.82E-01	1.54E-01
Ozone depletion	kg CFC-11 eq	8.76E-09	3.83E-08	7.77E-09	1.01E-08	9.45E-09	8.12E-09	9.72E-09	9.41E-09	8.11E-09	7.92E-09	1.13E-08	9.38E-09	8.13E-09	1.04E-08	8.89E-09	8.76E-09
Human toxicity, non-cancer effects	CTUh	4.77E-08	3.65E-08	4.48E-08	5.68E-08	5.24E-08	4.62E-08	4.98E-08	4.77E-08	4.76E-08	4.49E-08	5.61E-08	6.42E-08	3.12E-08	5.31E-08	4.81E-08	4.77E-08
Human toxicity, cancer effects	CTUh	3.72E-09	5.32E-09	3.30E-09	4.11E-09	4.07E-09	3.35E-09	4.28E-09	3.72E-09	3.72E-09	2.98E-09	5.94E-09	4.06E-09	3.39E-09	2.97E-09	3.85E-09	3.72E-09
Particulate matter	kg PM _{2.5} eq	5.60E-05	6.88E-05	4.29E-05	5.99E-05	6.11E-05	4.96E-05	6.57E-05	5.84E-05	5.36E-05	4.49E-05	8.94E-05	5.92E-05	5.29E-05	4.69E-05	6.18E-05	5.60E-05
Photochemical ozone formation	kg NMVOC eq	6.34E-04	6.97E-04	6.01E-04	6.90E-04	6.91E-04	5.56E-04	7.52E-04	6.77E-04	5.92E-04	5.08E-04	1.01E-03	6.51E-04	6.18E-04	4.28E-04	7.05E-04	6.34E-04
Acidification	molc H ⁺ eq	8.30E-04	9.44E-04	7.29E-04	9.03E-04	9.07E-04	7.35E-04	9.71E-04	8.64E-04	7.95E-04	6.66E-04	1.32E-03	8.89E-04	7.70E-04	6.33E-04	9.07E-04	8.30E-04
Terrestrial eutrophication	molc N eq	2.09E-03	2.08E-03	1.84E-03	2.34E-03	2.28E-03	1.88E-03	2.41E-03	2.26E-03	1.93E-03	1.79E-03	3.00E-03	2.29E-03	1.90E-03	1.74E-03	2.22E-03	2.09E-03
Freshwater eutrophication	kg P eq	2.41E-05	4.35E-05	1.91E-05	2.76E-05	2.63E-05	2.29E-05	2.58E-05	2.41E-05	2.41E-05	2.18E-05	3.10E-05	2.77E-05	2.05E-05	2.84E-05	2.51E-05	2.41E-05
Marine eutrophication	kg N eq	2.39E-04	2.08E-04	2.24E-04	2.71E-04	2.61E-04	2.20E-04	2.68E-04	2.54E-04	2.24E-04	2.11E-04	3.24E-04	2.74E-04	2.04E-04	2.02E-04	2.51E-04	2.39E-04
Freshwater ecotoxicity	CTUe	4.55E-01	4.06E-01	4.00E-01	5.27E-01	5.00E-01	4.42E-01	4.76E-01	4.56E-01	4.55E-01	4.29E-01	5.35E-01	5.95E-01	3.16E-01	6.89E-01	4.69E-01	4.55E-01
Water resource depletion	m ³ water eq	8.54E-04	1.17E-03	8.06E-04	9.91E-04	9.40E-04	7.90E-04	9.51E-04	8.55E-04	8.54E-04	7.26E-04	1.24E-03	8.73E-04	8.36E-04	7.76E-04	8.84E-04	8.54E-04
Mineral, fossil & ren resource depletion	kg Sb eq	8.76E-06	1.20E-05	6.15E-06	1.04E-05	9.61E-06	7.71E-06	1.03E-05	8.76E-06	8.76E-06	6.67E-06	1.50E-05	8.87E-06	8.65E-06	7.34E-06	8.77E-06	8.76E-06



Annex D: Seaweed production: 'cradle to gate' impact results

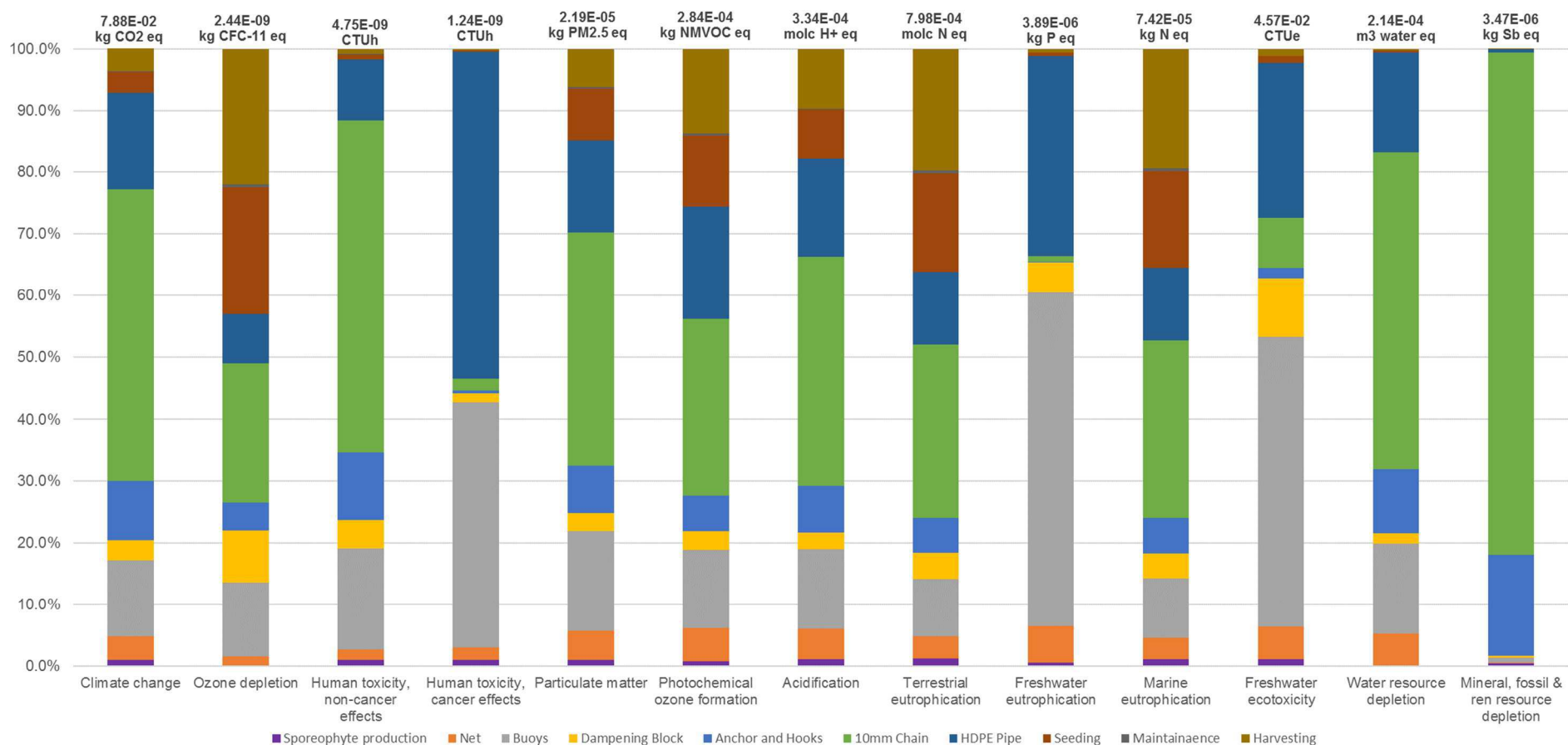


Figure D1 - Environmental impact results for cradle to gate production of 1 kg(ww) under the baseline scenario (total value shown above each column for each impact category)