eForFuel

PROJECT ACRONYM

eForFuel

PROJECT TITLE

Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons

Deliverable 5.5

Report on integrated sustainability assessment

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2	25/02/2022	Final version	Nils Rettenmaier, Guido Reinhardt

Cooperation between participants

This deliverable D5.5 "Report on integrated sustainability assessment" has been prepared by IFEU and presents the results of IFEU's work under Task 5.5. The integrated sustainability assessment was performed on the basis of the results obtained in Tasks 5.1, 5.2, 5.3 and 5.4 which were provided by AM (D 5.3) and IFEU (D 5.2 and D 5.4), respectively.

All partners contributed to this deliverable by reviewing the content of the whole document.

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Integrated Sustainability Assessment of Electro-Microbially Produced Transport Fuels

This report was produced as Deliverable 5.5 within Work Package 5 "Integrated sustainability assessment" of the EU-funded project eForFuel ("Fuels from electricity: de novo metabolic conversion of electro-chemically produced formate into hydrocarbons")

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Heidelberg, February 2022

Table of Contents

Index of Figures and Tables

1. Executive summary

The defossilisation of the transport sector is one of the major challenges in meeting the climate targets of the Paris Agreement. In contrast to other sectors, greenhouse gas (GHG) emissions from the transport sector in Europe continuously increased from 1990 to 2007 and, after a decline between 2008 and 2013, are on the rise again since 2014. They are projected to remain at a high level of around 1,100 Mt CO_2eq until 2035 if no additional measures were implemented [EEA 2021]. Over those three decades, extensive research was conducted on renewable fuels for transport. Biofuels, once a hopeful candidate, have experienced a rollercoaster development and are currently considered as not fully environmentally sustainable due to land use-induced impacts. Therefore, innovative renewable transport fuels that are independent of agricultural or forestry land use, have gained growing attention.

Among those fuel options are industrial biotechnology approaches in which microorganisms use CO_2 and renewable electricity as sole carbon and energy sources for the growth and production of renewable hydrocarbon fuels. A corresponding concept has been developed within the EU-funded eForFuel project ("Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons", GA ID: 763911). However, a novel concept for renewable fuel production does not automatically imply that the overall sustainability performance is better. Therefore, the R&D work in eForFuel included an integrated sustainability assessment, the results of which are presented here.

The aim of this study is to assess the potential environmental impacts associated with the implementation of the eForFuel concept in the future. The main objective of the study is to determine whether or under which conditions the eForFuel concept can contribute to a more sustainable supply of transportation fuels for passenger cars and aviation. Another important goal of the study is to identify optimisation potentials to determine focal areas for the further development of the eForFuel concept. To cover the full breadth of the concept, three different electro-microbial fuels were investigated. While the R&D work was conducted at TRL 4 and 5, this ILCSA is based on scenarios representing mature technology on industrial scale. The study follows the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015], joining the previous assessments of environmental, techno-economic as well as socio-economic and policy aspects into an overall picture and analyses them collectively to give an integrated view on the implications for sustainability associated with the eForFuel concept.

The main result of the study is that under the technical boundary conditions assumed, none of the eForFuel scenarios considered in the sustainability assessment proves to be economically viable. In terms of environmental impact, advantages compared to conventional fossil fuels can be achieved under ideal conditions - however, two preconditions must be met: (i) the emission factor of the electricity used must be very low (<15 g CO_2eq / kWh) and (ii) for the co-product oxygen, a credit must be obtained for (the avoided environmental impacts of) the replaced conventional oxygen. Furthermore, the eForFuel scenarios are associated with high social risks, which may even exceed the social risks associated with fossil fuels. However, this can only be reasonably assessed once social structures in the emerging European and international market have been established on a large scale. Compared to biofuels, under the rather optimistic boundary conditions of the typical scenarios, slight advantages for electro-microbial fuels are apparent for some indicators from the dimensions of environment and society - as long as the above-mentioned criteria regarding the emission factor for electricity and the oxygen credit are met. However, even in these cases, advantages are not achieved in all scenarios and across all indicators.

The enormously high specific electricity demand of the eForFuel concept, associated with high costs, social risks and environmental effects, has a very negative impact on the performance in all sustainability dimensions. Even though renewable resources often have a low environmental burden, they are not entirely 'burden-free' or 'CO_2-neutral'. However, if technical breakthroughs in the electroreactor and the bioreactor can (i) significantly reduce the enormously high specific electricity demand and (ii) improve the internal recycling of gases, electrolyte and water substantially, the eForFuel concept could unfold its potential and offer a renewable alternative to conventional, fossil or even to conventional as well as advanced biofuels.

It remains to be seen to what extent it will be possible to keep up with other, purely electrochemically generated e-fuels (for road, air and marine transport) or battery electric vehicles (only for road transport) in terms of sustainability performance. Under the currently assumed technical boundary conditions, the competitors would clearly be ahead - at least from an environmental point of view. Nevertheless, since the views on electro-microbial fuels, as expressed in a public perception survey conducted within the eForFuel project, were generally rather positive, especially if used in aviation, concepts such as eForFuel could indeed gain the support of the EU population.

In order to enter the fuel market, a number of regulatory sustainability requirements of the Renewable Energy Directive (RED II) have to be fulfilled. The lack of some important delegated acts within the context of RED II currently represents the greatest uncertainty for the eForFuel concept. This has a negative impact on the further technical development and possible later market launch: the fulfilment of the minimum GHG emission savings could not be verified, as both the calculation principles and the threshold value for Recycled Carbon Fuels (RCF) are missing.

The investigated concept of electrochemical CO_2 activation via reduction to formic acid, followed by microbial conversion to hydrocarbons, could possibly unfold its potential in other markets, where the strengths of fermentation in the flexible production of more complex and more highly oxidised molecules can be exploited better. Thus, it is conceivable to also address the area of classic bio-based products or even the food & feed market via proteins, for example.

From this analysis several stakeholder-specific recommendations were deduced which conclude this report.

Key deliverable achievements:

1. Assessment of potential implications for sustainability associated with a future implementation of the eForFuel concept successfully completed
2. Determination of the conditions under which the eForFuel concept can contribute to a more sustainable supply of transportation fuels for passenger cars and aviation
3. Identification of strengths, weaknesses, opportunities and threats of the eForFuel concept
4. Derivation of conclusions and recommendations with regard to the eForFuel concept

2. Introduction

The defossilisation of the transport sector is one of the major challenges in meeting the climate targets of the Paris Agreement. In this regard, biofuels have been promoted as renewable fuel options since more than two decades. However, there is clear evidence that biofuels are not fully environmentally sustainable, with the first LCA-type studies actually dating back 30 years ago [Reinhardt 1991]. As a consequence of the 'food vs. fuel debate' starting in the mid-2000s, the regulatory framework in Europe has been tightened several times by introducing sustainability criteria for biofuels [European Parliament & Council of the European Union 2009] and a limit for food and feed crop-based biofuels [European Parliament & Council of the European Union 2018]. Therefore, innovative renewable transport fuels - ideally independent of agricultural or forestry land use - have gained growing attention. Examples include advanced biofuels from ligno-cellulosic material and various types of renewable fuels that are not based on biomass but on renewable electricity, i.e. synthetic fuels / e-fuels / PtX fuels.

The EU-funded eForFuel project ("Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons", GA ID: 763911) has developed an industrial biotechnology solution in which microorganisms use CO_2 and (renewable) electricity as sole carbon and energy sources for growth and production of renewable hydrocarbon fuels (Figure 1). For this, electrochemical (carbon dioxide activation via reduction to formic acid) and microbial conversions (production of hydrocarbons via formatotrophic bacteria) are combined in an electro-biorefinery.

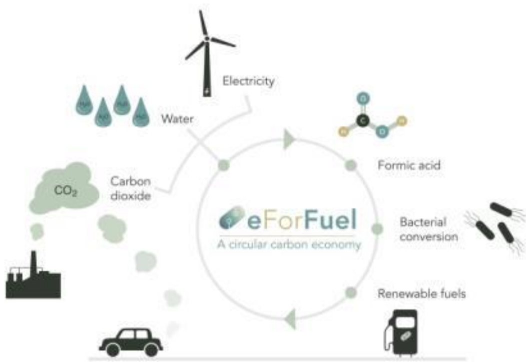

Figure 1: The eForFuel concept

The electro-microbial fuels obtained in this way would be and are envisioned to serve as a renewable alternative to fossil fuels in the EU's transport sector, helping to reduce greenhouse gas emissions and improve the EU's security of supply.

However, a novel concept for renewable fuel production does not automatically imply that the overall sustainability performance is better. Therefore, the R&D work in eForFuel includes an integrated life cycle sustainability assessment (ILCSA) to assess potential sustainability impacts associated with the implementation of the eForFuel concept in the future. The integrated sustainability assessment in eForFuel is based on a life cycle approach, taking into account the entire life cycle 'from cradle to grave', including all co-products.

This 'Report on integrated sustainability assessment' (Deliverable D5.5) joins the previous specific assessments of environmental, techno-economic as well as socio-economic and policy aspects [Rettenmaier et al. 2021; Peleman & Van der Stricht 2021; Keller et al. 2021] into an overall picture and analyses them collectively to give an integrated view on the implications for sustainability associated with the eForFuel concept. Methodological details are summarised in chapter 3, followed by a description of the analysed systems in chapter 4. Results are presented in chapter 5 and 6. Finally, chapter 7 provides conclusions and recommendations regarding the sustainability of the production and use of electro-microbial fuels.

3. Methods

The integrated sustainability assessment in eForFuel follows the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015], which is briefly introduced in section 3.1. As a prerequisite for this, common goal and scope definitions and other common settings are imperative which apply equally to the environmental, techno- economic and social assessment. Only then can the results of these individual assessments, which always have to be interpreted against the background of the underlying (common) goal and scope definitions, be combined in a meaningful way. These common definitions and settings are described in section 3.2. Specific definitions and settings that are only relevant for the environmental, economic, social and policy assessment can be found in the respective reports [Rettenmaier et al. 2021; Peleman & Van der Stricht 2021; Keller et al. 2021] whereas specific definitions and settings for the integrated sustainability assessment are described in section 3.3.

3.1. ILCSA methodology in a nutshell

The analysis of the life cycles within eForFuel follows the integrated life cycle sustainability assessment (ILCSA) methodology (Figure 2). The methodology, described in detail in [Keller et al. 2015], builds upon existing frameworks. It is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP/SETAC guidelines for social life cycle assessment [Andrews et al. 2009][1]. ILCSA extends them with features for ex-ante assessments such as the identification of implementation barriers that increase the value for decision makers. This flexibility allows for focussing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. Furthermore, it introduces a structured discussion of results to derive concrete conclusions and recommendations. See section 3.3 for details on the procedure selected in this study.

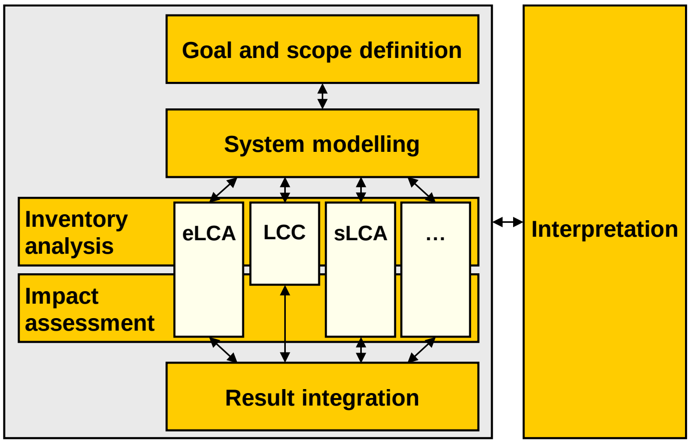

Figure 2: Structure of the integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015].
It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle assessment, (e)LCA, life cycle costing, LCC, social life cycle assessment, sLCA and analyses of other sustainability-relevant aspects.

[1] Meanwhile superseded by [Benoît Norris et al. 2020]

3.2. Common definitions and settings

Common general definitions and settings are important for an efficient professional communication between the project partners in WP 5 and ensure consistent data and results for the integrated sustainability assessment. For an extensive overview of the definitions and settings and for an early system description (superseded by the system description in chapter 4), see [Rettenmaier et al. 2019, Deliverable D 5.1]. The goal and scope definition is the first phase of any sustainability assessment and is relevant for all three sub-analyses on the environmental, economic and social impacts. In the following sections, these definitions and settings are summarised as far as they are relevant for the integrated sustainability assessment.

3.2.1. Goal definition

The comprehensiveness and depth of detail of the sustainability assessment can differ considerably depending on its goal. Therefore, the intended applications, the reasons for carrying out the study, the decision context as well as the target audiences and the commissioner have to be described within the goal definition.

Intended applications and goal questions

The sustainability assessment within the eForFuel project aims at two separate applications:

1) Project-internal support of ongoing process development.
   This makes this study an ex-ante assessment because the systems to be assessed are not yet implemented in this particular form on a relevant scale and for a sufficiently long time.

2) Provision of a sound basis to communicate findings of the eForFuel project to external stakeholders, i.e. science and policy makers. Exemplary statements aimed at:

   - Policy information: Which product chains have the potential to show a low sustainability impact?
   - Policy development: How could new / adapted policies guide developing raw material production strategies to increase advantages and avoid disadvantages?

In this context, a number of goal questions have been agreed upon by the eForFuel consortium. Their purpose is to guide the sustainability assessment in WP5. The goal questions are listed in the following, starting with the **main question**:

- How and under which conditions can the eForFuel concept (metabolic conversion of electrochemically produced formic acid) contribute to a more sustainable supply of transportation fuels for passenger cars and aviation?

This main question leads to the following sub-questions:

- Which life cycle stages or unit processes dominate the results significantly and which optimisation potentials can be identified?
- Do some eForFuel value chains show a better life cycle sustainability than others?
- Which trade-offs *within* and *between* the pillars of sustainability (environment, economy, society) may arise?
- How far does the further processing of formic acid improve sustainability and could its direct use in fuel cells represent an alternative / first implementation step?
- What is the influence of possible transitions in the economy (e.g. renewable energy, oil price)?

- Which technological, raw material supply-related or other potential barriers may hinder the large-scale industrial deployment?
- Do the eForFuel value chains comply with the sustainability criteria set out in the Renewable Energy Directive (I and II)?

Target audience

The definition of the target audience helps identifying the appropriate form and technical level of reporting. The target audience is divided into i) project partners and ii) external stakeholders (scientists, EC staff, political decision makers, interested laypersons).

Reasons for carrying out the study and commissioner

The life cycle assessment is carried out because the eForFuel consortium has decided to supplement the development of its industrial biotechnology solution of producing of renewable hydrocarbon fuels with a corresponding analysis. The study is financially supported by the EU Commission, which signed a grant agreement with the eForFuel consortium.

3.2.2. Scope definition

With the scope definition, the object of the sustainability assessment (i.e. the exact product or other system(s) to be analysed) is identified and described. The scope should be sufficiently well defined to ensure that the comprehensiveness, depth and detail of the study are compatible and sufficient to address the stated goal. Resulting definitions and settings are used in the subsequent analyses (tasks) to guarantee the consistency between the different assessments of environmental, economic and social implications.

System boundaries

System boundaries specify which unit processes are part of the production system and thus included into the assessment. The sustainability assessment of the eForFuel system takes into account the products' entire value chain (life cycle) from cradle to grave, i.e. from resource extraction to the utilisation and end of life of the products (Figure 3). For the equivalent conventional reference products, the entire life cycle is taken into account, too. This setting was chosen because the concept of life cycle thinking integrates existing consumption and production strategies, preventing a piece-meal approach. Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium or protection target to another.

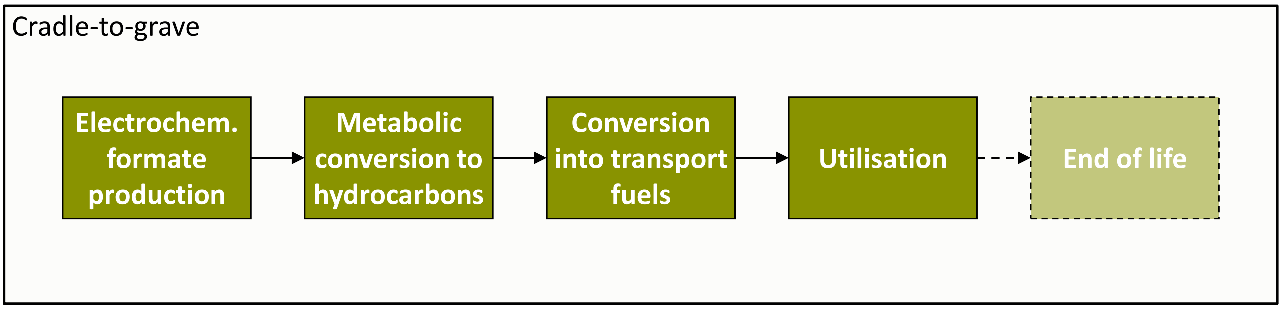

Figure 3: System boundary (cradle-to-grave) applied within the eForFuel project.

Geographical coverage

Geography determines several background data sets used such as on prices or electricity mixes. For the sustainability assessment in eForFuel, EU27 is chosen because this makes the results most valuable for European decision-makers to evaluate the performance and consider next steps. Calculations are based on generic European datasets to the greatest extent possible.

Some parameters such as wages or energy prices are country-specific and vary across Europe. For the techno-economic assessment and the social and policy assessment, it is not meaningful to use European average values. Therefore, example countries were suggested for those assessments. Regarding country-specific electricity mixes, Spain (photovoltaics, PV) and Denmark (wind) are suggested as a starting point for exemplary analyses because of their potential for producing renewable electricity. Belgium is because of project partner ArcelorMittal's steel plant in Ghent.

For the LCA, country-specific datasets were not chosen. Instead, the impact of electricity is mainly evaluated in the form of 100% mixes (e.g. 100% wind, 100% PV).

Technical reference

The technical reference describes development status, maturity and scale. The sustainability assessment is carried out for mature technology on industrial scale ('nth plant').

Regarding the scale of the plant, the following capacities are selected for the electroreactor:

- 20 MW
- 100 MW
- 1,000 MW

Time frame

Like the geographical coverage (see above), the time frame of the assessment determines background datasets used. The year 2030 was selected as first realistic year in which the technology could be mature and available.

Analysed systems and settings for system modelling

A scenario-based assessment is applied. The analysed scenarios will represent realistic potential future implementations of the assessed technologies. When deriving the mass and energy flow data for these generic scenarios, data obtained from project partners' experiments, databases and literature was taken into consideration, but in most cases not be used directly (i.e. only after extrapolation). Uncertainty and future freedom of choice are covered by applying ranges of values from 'conservative' via 'typical' to 'optimistic'. Each scenario represents a complete life cycle from cradle to grave, i.e. one specific combination of options for each processing step.

To allow for provision of sound data and thorough analysis, three main scenarios are selected and less than 20 variations depicted in further scenarios. These are described in chapter 4. According to the DoA, all scenarios are assessed by LCA, techno-economic assessment and socio-economic and policy assessment.

Data sources

The sustainability assessment of the eForFuel scenarios requires a multitude of data. Primary data (on the foreground system) stems from the project partners:

- Electroreactor: University of Stuttgart (USTUTT), SINTEF AS, University of Alicante (UA)
- Bioreactor: Max Planck Institute of Molecular Plant Physiology (MPG), b.fab GmbH (BFAB)
- Product separation: Global Bioenergies (GBE)

All primary data were checked for plausibility by IFEU. Based on the mass and energy flow data, graphical mass and energy flow diagrams were created by C3 Biotechnologies Ltd (see chapter 10 in the annex).

3.3. Specific definitions and settings for ILCSA

The integrated sustainability assessment in eForFuel is based on the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015]. In the following sub-sections, specific settings and methodological choices are detailed.

3.3.1. General approach

There are two general options to integrate a multitude of indicators on certain scenarios:

- Weighting and mathematical integration
  All indicators could be mathematically combined into one score using weighting factors or ranked otherwise according to a weighting algorithm. These approaches, in particular the required weighting factors or schemes, cannot be entirely based on scientific facts but depend on personal value-based choices defined beforehand. Furthermore, conflict situations do not become apparent and decisions regarding these conflicts depend on weighting factors, which are hard to understand for decision makers not involved in the study. Therefore, this approach is not applied.
- Structured discussion
  All strengths, weaknesses and conflicts of the options can be discussed verbally argumentatively. This can make conflicts transparent and enable their active management. Considering the amount of options and indicators, this requires a structured approach. This approach is followed in this study. This section describes the methodology used for the structured comparison and presentation of decision options based on a multi criteria analysis.

3.3.2. Collection of indicators and results

Indicators and results for all scenarios are provided by the parallel assessments of individual sustainability aspects [Rettenmaier et al. 2021; Peleman & Van der Stricht 2021; Keller et al. 2021]. They are collected in overview tables. In some cases, indicators are selected or aggregated by the authors of the respective individual assessment to focus on the most relevant aspects for decision support.

The integrated sustainability assessment of this project is based on:

- 9 quantitative environmental indicators from life cycle assessment
- 1 quantitative economic indicator
- 5 quantitative and 1 qualitative social indicators

These are a subset of all possible indicators, which were assessed in previous steps of the sustainability assessment and found to be relevant for the decision process. No further adjustments are made except for rescaling quantitative data to a common basis if necessary. Thus, all specific settings, methodological choices including underlying estimates, and data sources apply unchanged as documented in the respective reports.

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly. Green boxes represent overall advantageous results, i.e. an improvement compared to a situation without eForFuel. Orange and red boxes represent overall disadvantages, i.e. a deterioration compared to a situation without eForFuel. Yellow boxes represent a minor sustainability impact. This way of categorising results supports the identification of options that perform best among all studied options but also maintains the quantitative information on the sustainability of a scenario. Results are collected for all assessed main scenarios. Additional results such as from sensitivity analyses based on dedicated scenarios, which are only relevant for one aspect of sustainability, are not collected. Results from these very specific analyses, e.g. identified boundary conditions that are necessary to reach the environmental performance of a certain main scenario, are part of the result summaries in chapter 5. They are taken into account for the overall conclusions and recommendations (chapter 6.1).

3.3.3. SWOT analysis

After the evaluation of the collected individual sustainability indicator values in the overview tables (see section 3.3.2), a SWOT analysis is carried out. A SWOT analysis is a tool to assess the performance of any venture, whether it is a project, a product or a company. It is increasingly used to describe the advantages and disadvantages of technologies and policies, including biorefinery concepts. It originates from business management and is a strategic planning tool to identify and assess the Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) of the system under study. Strengths and weaknesses are defined as internal characteristics of the assessed system, while opportunities and threats are external factors, determining the success or failure of the venture. The results of a SWOT analysis are generally summarised in a SWOT matrix. The general structure of a SWOT matrix is shown in Table 1.

Table 1: Structure of a SWOT analysis.

	Helpful	Harmful
Internal	Strengths	Weaknesses
External	Opportunities	Threats

Before performing the analysis, a definition of what is internal and what is external to the assessed system is needed. In the SWOT analysis for eForFuel, internal and external factors were distinguished as follows:

- **Internal**: all aspects which relate to intrinsic and demonstrated properties of the eForFuel system at typical technology development (e.g. electro-microbial production of fuel products, electricity sources used and their upstream provision etc.).
- **External**: all those aspects, which relate to expected future developments in economy, society, technology etc. (e.g. prices, demand, availability of renewable electricity, acceptance, subsidies, laws etc.), including expected technological developments (e.g. increased electroreactor efficiencies, yields etc.)

The aim of the SWOT analysis is to derive key findings for the integrated sustainability assessment. The main objective is to identify general strengths and weaknesses of the eForFuel concept as well as common or opposing trends between the environmental, economic and social sustainability aspects. Furthermore, external opportunities and threats for/to the system shall be defined. Based on this, key findings, conclusions and recommendations can be derived in an overall comparison (see section 3.3.4).

3.3.4. Overall comparison

Prior to the overall comparison of the results, the integrated life cycle sustainability assessment methodology typically includes a benchmarking step, in which all scenarios are benchmarked to one selected scenario. The aim of this step is to obtain a comprehensive overview of the sustainability advantages and disadvantages of the different scenarios compared to a baseline scenario. Due to the moderate number of scenarios analysed in this study, all relevant differences between the scenarios can already be clearly identified and categorised on the basis of an overview table. Consequently, the present study does not include a benchmark step. Instead, a SWOT analysis was performed (see previous section 3.3.3) which supports the derivation of conclusions and recommendations by identifying and interpreting commonalities and opposing effects from the different sustainability perspectives (environment, economy, society and policy).

For the overall comparison, a verbal argumentative discussion of decision options is supported by a structure table containing an overview of the original indicator results. For understandable reasons, the overview table can only show the final results for the individual indicators, but not the single contributions to these final results. However, the deduction of recommendations from the overview table does require further in-depth analyses and knowledge of the contributions e.g. of life cycle stages or unit processes that lead to these final results. For this reason, decisive background information from the contribution analysis are provided in in the text (e.g.: Differences A, B and C, are caused by the input of substance X in process Y; therefore input X should be reduced as far as possible.). This way, the overview table as well as a SWOT matrix provide additional insight, support the discussion, help not to miss any relevant aspect and make recommendations comprehensible.

4. Analysed systems

The systems that were decided upon in the course of the project are presented in the following. They provide the basis for the life cycle assessments. The three main routes are shown in section 4.1. Afterwards, the most important process blocks are presented individually and in more detail (sections 4.2 – 4.5), before reference scenarios and alternative scenarios are described in sections 4.6 and 4.7, respectively. Finally, section 4.8 summarises all investigated scenarios in an overview.

4.1. Main routes

Simplified schemes of the metabolic conversion of electrochemically produced formic acid into hydrocarbons are depicted in Figure 4 and Figure 5 for isooctane / isododecane (jet fuel) and propane, respectively. These are the three main routes investigated in eForFuel.

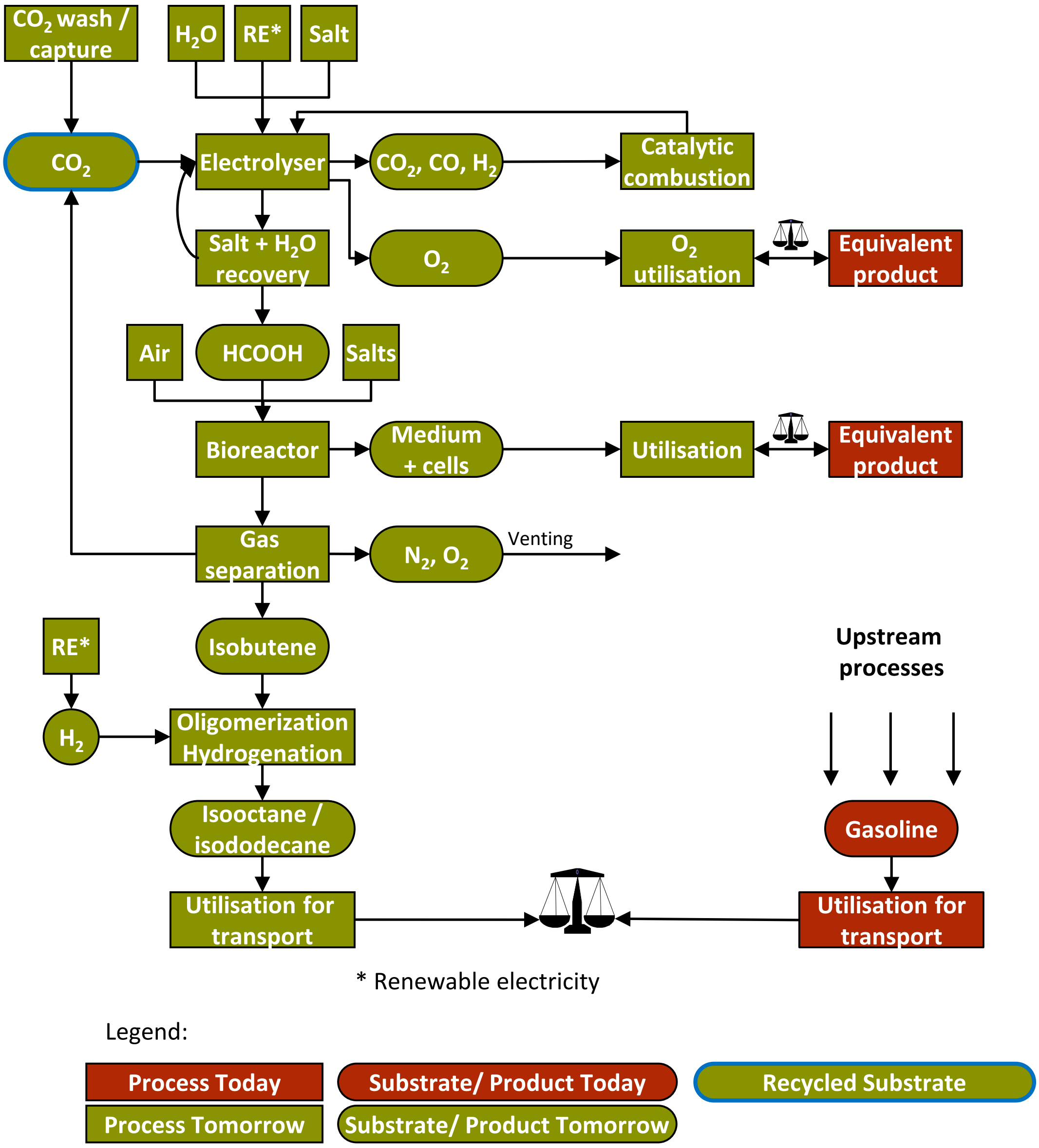

Figure 4: Simplified scheme of the isooctane route

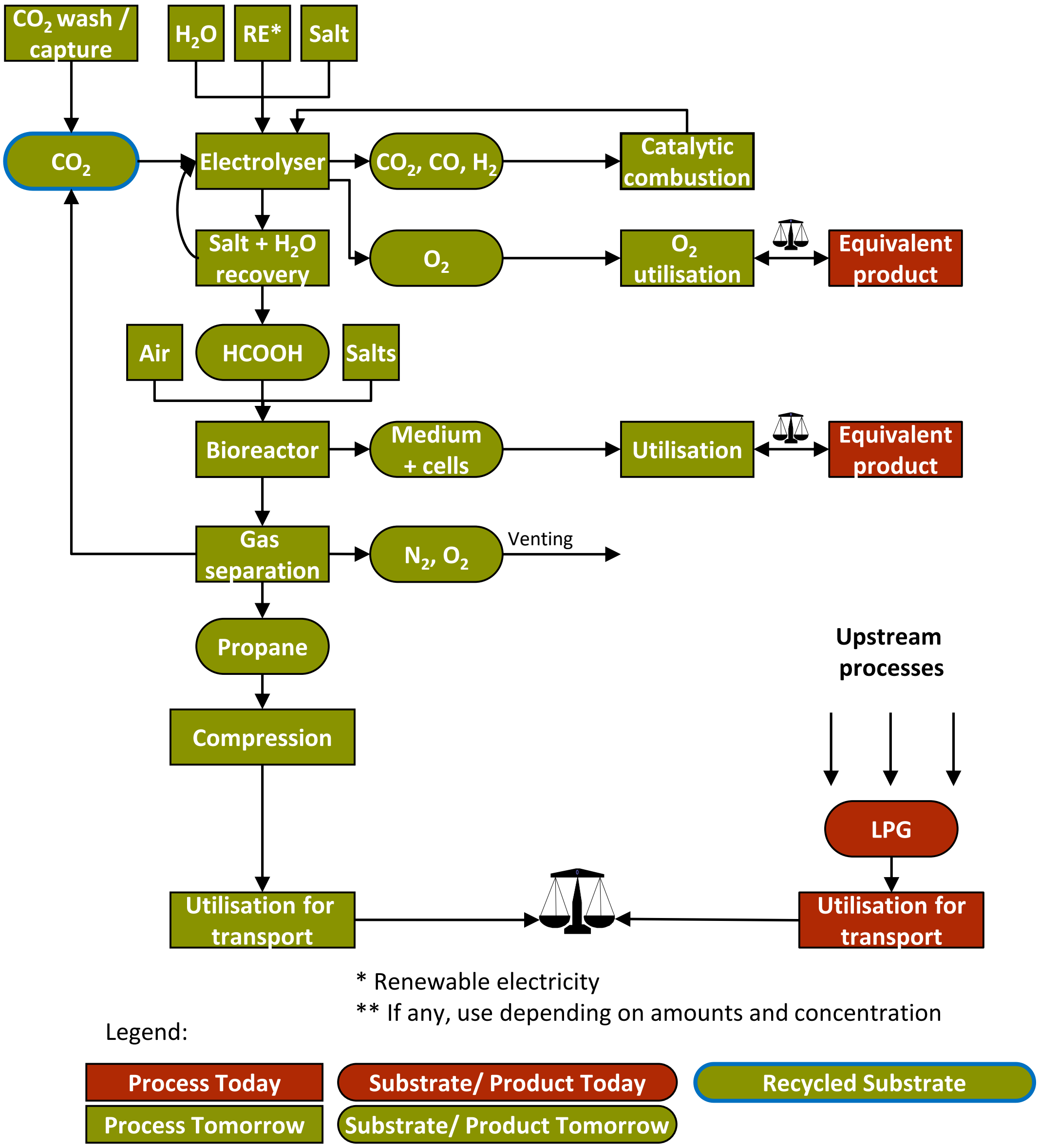

Figure 5: Simplified scheme of the propane route

4.2. Electrochemical production of formic acid (electroreactor)

The electrochemical production of formic acid (Figure 6) involves **inputs** of CO_2, renewable electricity (RE), de-ionised water (H_2O), salt/electrolyte (potassium sulphate, K_2SO_4), membrane and electrodes (cathodes and anodes). Membrane and anode form a membrane electrode assembly consisting of a catalyst-coated membrane and a porous transport layer. The catalyst and thus the anode are based on iridium oxide (IrO_2). This assembly has a lifetime of 4,000 to 40,000 hours. The cathode is tin-based, supported on acetylene black carbon with an expected life time of 50-2,000 hours. Iridium (Ir) from anodes will be recycled according to established procedures. Tin (Sn) from cathodes is recycled as well.

The ideal operating temperature of the electroreactor is 50 °C at a pressure of 1 bar. At this operating temperature, cooling is required to remove the co-produced heat. The **outputs** consist of formic acid (HCOOH), spent membranes and electrodes, oxygen (O_2) at the anode and a gas mixture of CO_2, carbon monoxide (CO) and hydrogen (H_2) at the cathode. The cathode gas mixture is catalytically combusted with O_2 from the anode, forming CO_2 and H_2O, which are recycled to the electroreactor. The remaining O_2 from the anode is set to replace O_2 from an air separation unit (ASU). The formic acid is dissolved in the brine (water and potassium sulphate, K_2SO_4). Part of the K_2SO_4 will be recovered via electrodialysis. The co-produced heat from the electrodialysis needs to be removed from the system as well. At an operating temperature of 50 °C, the temperature level of the co-produced heat is too low for direct use. However, it can be used as a heat source for district heating when raising the temperature level to 90 °C with a heat pump. The power saved compared to a heat pump using an ambient temperature heat source is credited.

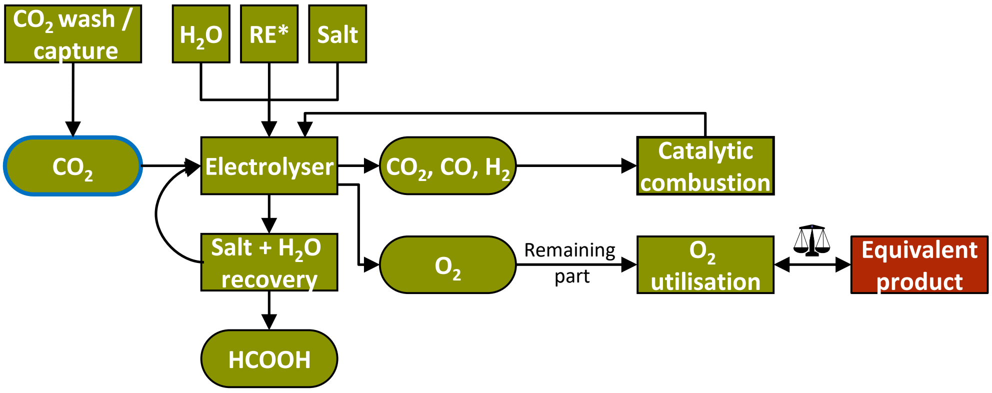

Figure 6: Electrochemical production of formic acid

4.3. Metabolic conversion into hydrocarbons (bioreactor)

The formic acid (HCOOH) produced in the electroreactor is transferred to a bioreactor where it is metabolically converted into either propane or isobutene (Figure 7). Apart from formic acid, **inputs** of air, water (H_2O), salts (ammonium, phosphate and sulphate salts) and further nutrients such as yeast extract are required. The operating temperature is 37 °C and the pressure in the bioreactor is 1 bar. Credits for this low temperature heat source are given similar to the electroreactor. **Outputs** include spent medium + cells (use: anaerobic digestion yielding bioenergy + fertiliser), water (from reaction and losses through evaporation) and a gas mixture. The cells need to be inactivated as they are genetically modified organism (GMO). A thermal inactivation is set as the typical treatment. The gas mixture is separated into CO_2 (recycled to electroreactor), exhaust gas (O_2, N_2, H_2O) and propane, or respectively isobutene. The separation is carried out in a two-stage process, first the separation of the propane or isobutene and then the recovery of the CO_2 with an amine wash (see also section 4.5.2).

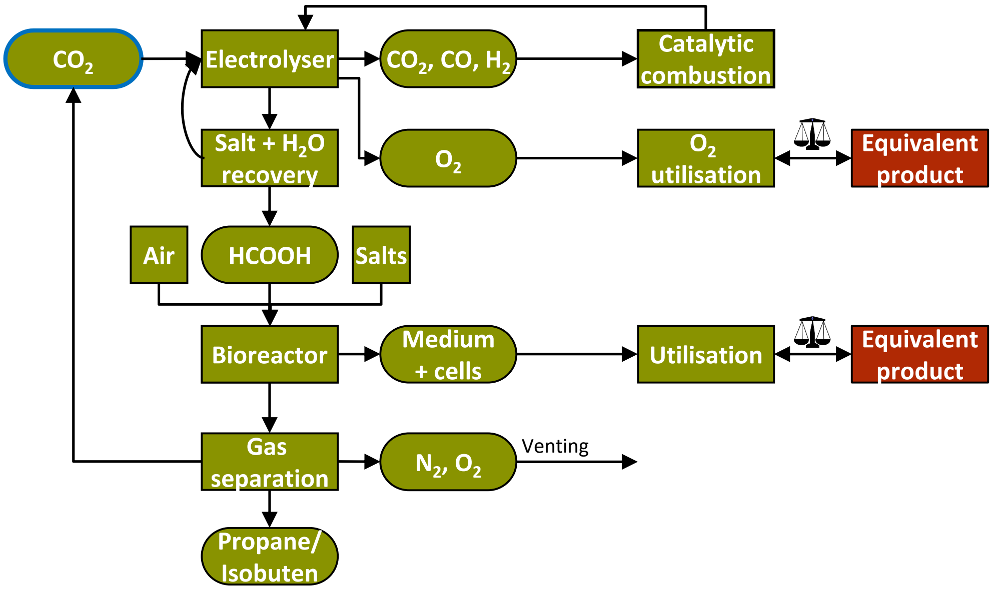

Figure 7: Metabolic conversion of formic acid into hydrocarbons

4.4. Conversion into transport fuels

Conversion into hydrocarbon fuels for passenger cars is fairly straightforward. For the oligomerisation and hydrogenation of isobutene into isooctane, hydrogen (H_2) and a part of the isooctane output (reused in the oligomerisation reactor to absorb heat) are required as an **input**. For propane, energy is needed for compression. In terms of **outputs**, as co-product of isooctane also isododecane is formed (Figure 8). Credits for this low temperature heat source are given similar to the electroreactor.

For the production of isododecane from isobutene, the same inputs are needed. Besides isododecane, also isooctane and isobutane are formed as outputs.

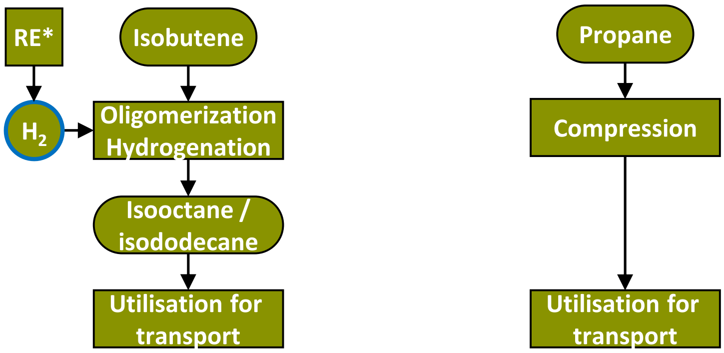

Figure 8: Conversion of gaseous intermediates (isobutene and propane) into hydrocarbon fuels

4.5. Sources of main inputs

From preliminary calculations performed during the proposal writing phase, it became clear that the results of the environmental assessment (LCA) will be mainly determined by the exact nature / source of three main inputs: electricity, heat, CO_2 and hydrogen.

4.5.1. Electricity source

The main source of electricity will be **renewable electricity** from either wind or photovoltaics (PV). Both are fluctuating/intermittent renewables. Since the exact environmental footprint of electricity provision in 2030 is unknown, four exemplary renewable electricity sources are defined for sensitivity analysis. Wind energy from offshore and onshore wind parks is considered, as well as electricity from ground-mounted photovoltaic (PV) systems in two different geographical locations of Europe (Southern Europe: Lisbon: Central Europe: Munich). This is to account for different intensities of solar irradiation. Moreover, the average European grid mix in 2030 is defined to represent the case of using eForFuel technology as a transition technology or the case that not enough renewable energy can be provided.

Instead of using high amounts of renewable electricity for the eForFuel system, the same electricity could be used directly in electric cars (with some grid stabilising technology such as battery storage in between). This will be investigated in an alternative scenario (see chapter 4.7).

4.5.2. Heat source

The heat required for CO_2 capture, thermal inactivation of the GMOs and product separation after the bioreactor is provided from electricity (power-to-heat, PtH) in the baseline scenario. Additionally, biomass heat plants and the combustion of natural gas are compared in a sensitivity analysis.

4.5.3. CO_2 source

The main source of **CO_2** in eForFuel will be blast furnace (BF) gas **from steel plants** with a typical CO_2 concentration of ~25%. CO_2 will be separated from BF gas by aqueous monoethanolamine (MEA) solution. The removal of CO_2 from the BF gas leaves the energy content of the BF gas largely unchanged but reduces its volume. The resulting energy savings are set zero since they are minor.

Since the emission of (fossil) CO_2 from the steel plant (either directly or indirectly after the second life as fuel) leads to an increase of atmospheric CO_2 levels, **CO_2 from direct air capture (DAC)**, which keeps the atmospheric CO_2 levels constant, will be investigated as an alternative. Moreover, **biogenic CO_2** from fermentation or anaerobic digestion (+methanation) is considered as further alternative.

4.5.4. Hydrogen source

The main source of hydrogen (H_2) will be **hydrogen from PEM water electrolysis**, using renewable electricity. The co-product O_2 is released to the atmosphere.

4.6. Reference scenarios

For the comparison of the eForFuel systems, the definitions of the reference systems are required. They depict alternatives that would likely be in place if eForFuel would not be realised.

Reference products

The (conventional) reference product represents the product that is replaced by the eForFuel value chain. The appropriate definition of the reference products is an essential part of the life cycle comparison approach. It highly affects the sustainability results of a given system to be investigated. In the eForFuel project, the reference products for the main products (fuels) are both petroleum- and biomass-based:

- Liquefied petroleum gas (LPG; main reference for propane)
- Gasoline (main reference for isooctane)
- Jet A-1 fuel (main reference for isododecane)
- Bioethanol (1G / 2G) as additional reference for isooctane
- Fischer Tropsch (FT) bio jet fuel as additional reference for isododecane

For biofuels, GHG emissions related to land use (LU) and land use change (LUC) are taken into account.

4.7. Alternative scenarios

It is clear from many studies on the transformation into a low carbon society that the availability of renewable electricity may well become a critical aspect. Therefore, eForFuel could be compared to alternatives that could use the same renewable electricity to provide the same mobility service:

1. The intermediate product formic acid could also be used directly in a fuel cell vehicle after concentration e.g. via electrodialysis and distillation.
2. Renewable electricity could be used in other non-biological PtX processes yielding hydrogen, methane or methanol as transportation fuels.
3. Renewable electricity could be used directly in electric cars (with some grid stabilising technology such as battery storage in between).

This idea has only been taken up in the environmental assessment [Rettenmaier et al. 2021], in which alternative scenario 3 was analysed. Therefore, it was not taken up as a scenario in this ILCSA study.

4.8. Overview of scenarios

Table 2 lists the scenarios investigated in this ILCSA study which were selected in an early phase of the eForFuel project [Rettenmaier et al. 2019]. The scenario using blast furnace gas from steel plants as CO_2 source for the production of isooctane with gasoline as reference product is defined as the 'baseline scenario'. The alternative scenario (direct use of renewable electricity in battery electric vehicles, BEV) was only analysed in the environmental assessment.

Table 2: List of scenarios for analysis in WP 5. Variations from main scenarios are highlighted in blue.

		CO_2 source	Fuel product	Reference fuel
eForFuel scenarios	Main 1	Steel plant	Propane	LPG
	Main 2 (Baseline)	**Steel plant**	**Isooctane**	**Gasoline**
	Main 3	Steel plant	Isododecane	Jet fuel
		DAC*	Propane	LPG
		DAC*	Isooctane	Gasoline
		DAC*	Isododecane	Jet fuel
		Biogenic	Propane	LPG
		Biogenic	Isooctane	Gasoline
		Biogenic	Isododecane	Jet fuel
		Steel plant	Isooctane	1G Bioethanol
		Steel plant	Isooctane	2G Bioethanol
		Steel plant	Isododecane	FT# bio jet fuel
Alt. scen.	Electric car (BEV)	n.a.	n.a.	Gasoline/ diesel

* Direct air capture, # Fischer-Tropsch, FT biofuel is also known as biomass to liquid (BtL)

Apart from the CO_2 source, also other parameters are varied. Figure 9 illustrates the various combinations of influencing parameters. The settings for the 'baseline scenario' – marked in bold in Figure 9 – are chosen to represent a realistic future situation. Isooctane is an alternative to gasoline. Electricity is supplied by offshore wind farms. Heat is supplied by power-to-heat from offshore wind farms in the sense of sector coupling. CO_2 is captured from blast furnace gas from steel plants.

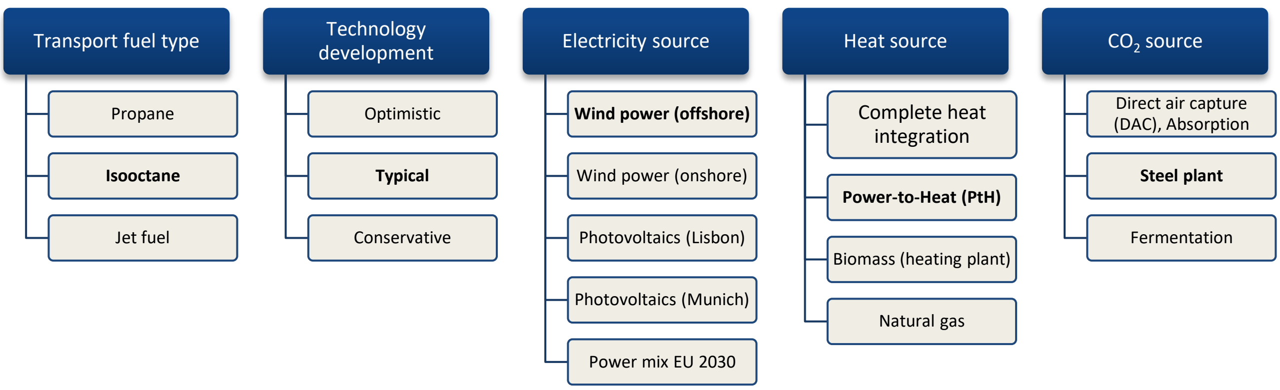

Figure 9: Influencing factors and possible settings for the analysed electro-microbial production of transport fuels. The settings of the baseline scenario are marked in bold.

5. Summaries of specific assessments

As a basis for further analyses, this chapter contains summaries of the assessments of individual sustainability aspects (sections 5.1 - 5.3).

5.1. Summary: environmental life cycle assessment

A screening life cycle assessment was carried out, analysing the environmental implications of the scenarios described in chapter 4. For a summary on the applied methods and further details please refer to the report on life cycle assessment (LCA) [Rettenmaier et al. 2021].

Figure 10 exemplarily shows the normalised LCA results for all impact categories for the baseline scenario producing isooctane. The figure shows burdens caused by the eForFuel value chain on the right hand side and credits that are assigned due to the substituted conventional reference products on the left hand side. The narrow white bar in the middle of each bar indicates the net result.

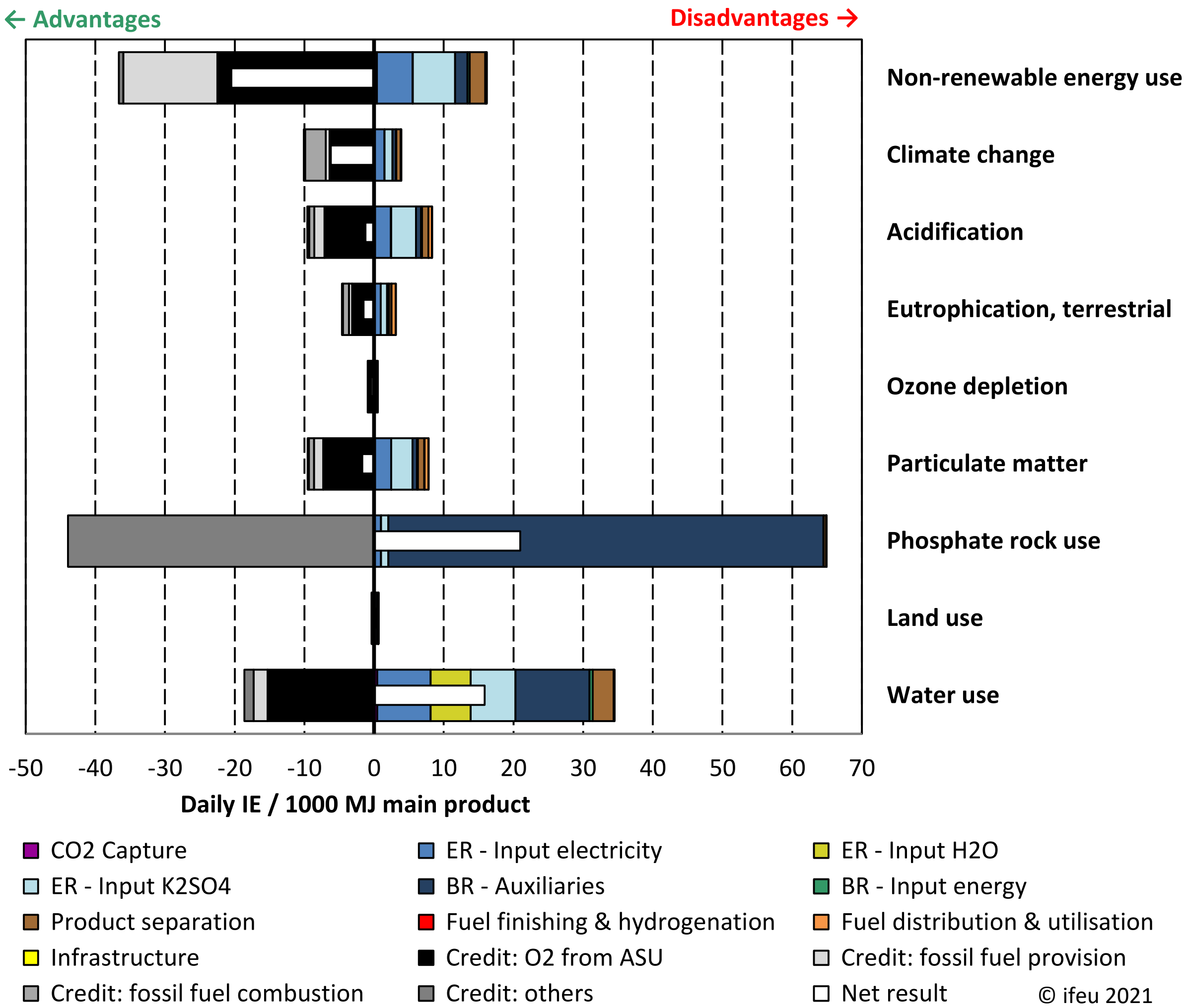

Figure 10: Normalised LCA results (given in inhabitant equivalents (IE)) for all impact categories for the baseline scenario*

How to read the figure: The sections on the right hand side of the 2nd bar illustrate that the production of isooctane equivalent to 1000 MJ in a process corresponding to the baseline scenario and the following usage causes GHG emissions roughly equal to the emissions an average EU citizen emit in 4 days. Similarly, the credits correspond to the GHG emissions of an EU citizen in approximately 10 days. In summary, the emissions of about 6 days can be saved.

* Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.

Figure 10 reveals that the baseline scenario leads to net advantages for eForFuel in the impact categories 'non-renewable energy use' and 'climate change', since the credits for avoided burdens (advantages) clearly outweigh the emissions (disadvantages). For the categories 'phosphate rock use' and 'water use', the disadvantages predominate for electro-microbial fuels. For all other impact categories, including 'land use', the two alternatives, electro-microbial fuels and fossil fuels, achieve comparable results.

For an overview of all analysed scenarios Figure 11 presents the net results of all impact categories and fuel types related to inhabitant equivalents (IE) for the best-case and the worst-case scenario as well as the scenario involving energy sources other than renewable electricity.

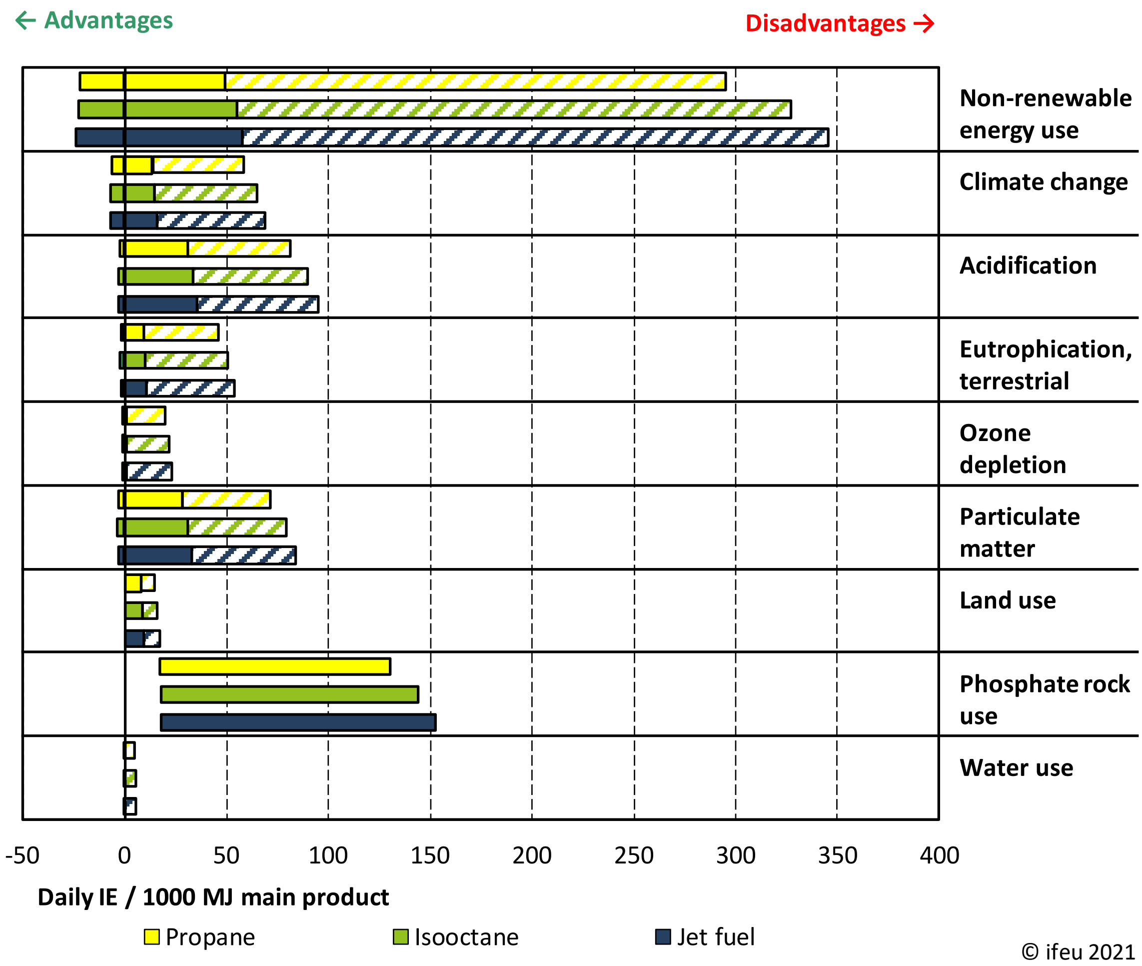

Figure 11: Ranges of normalised environmental impacts for electro-microbially produced transport fuels.
How to read the figure: All environmental impacts are normalised to daily inhabitant equivalents (IE) per 1000 MJ electro-microbially produced fuel. Different colours correspond to different fuel types. Combining the best-case and worst-case scenario results in a range of possible scenarios for which the eForFuel project is aimed (completely filled bar sections). The shaded bar sections shows the range of possible scenarios involving energy sources other than renewable electricity.

For all impact categories assessed, with the exception of land use, the use of phosphate rock and the water use, the production and use of electro-microbial fuels can be advantageous or equivalent to fossils in the best case. For phosphate rock use, fossil fuels are far superior to electro-microbial fuels in all cases. For all scenarios closer to the worst case scenario, the environmental impacts of electro-microbial fuels are unfavourable compared to fossil fuels. The comparison of the three fuel types reveals that the environmental impact of these fuels hardly differ in the best-case scenario. For scenarios close to the worst-case scenario, jet fuel production is associated with more disadvantages than isooctane and propane production. Scenarios involving energy sources other than renewable electricity show significantly more negative environmental impacts than the worst-case renewable scenario. The only exception is the 'phosphate rock use', because the need for phosphate rock for the photovoltaic plant production leads to a higher phosphate rock footprint in case of photovoltaic power than in case of the power mix EU 2030.

These results can be summarised as follows:

- The environmental impact of electro-microbial fuels varies greatly depending on the scenario.
- Advantages over fossil fuels are only to be expected in scenarios close to a best-case scenario.
- The eForFuel technology should not be combined with non-renewable energy sources.

One goal of the eForFuel project was to develop processes for the production of renewable hydrocarbon fuels that are more environmentally friendly than biofuels. For example, instead of using electro-microbial isooctane as an alternative to fossil gasoline, also other renewable transport fuels such as bioethanol could be used. Moreover, instead of using internal combustion engines vehicles (ICEV) the power-train could be changed in electric cars (battery electric vehicles, BEV). Figure 12 compares the range of environmental impacts of these three alternatives in categories typically associated with renewable energy, i.e. climate change, phosphate rock use, land use and water use. The range for bioethanol originates from different crops that can be used for production, and for electric cars from both different sources of electricity (including even non-renewable energy, analogous to the eForFuel scenarios) and battery capacities.

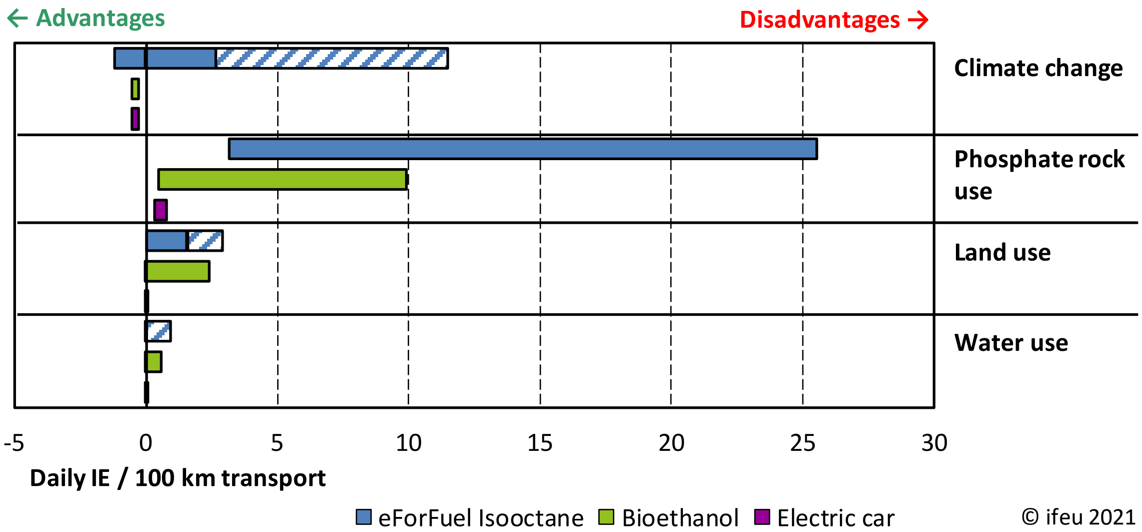

Figure 12: Comparison of electro-microbially produced isooctane to bioethanol and electric cars for different environmental impact categories.* **How to read the figure:** The first three bars show the range of GHG emissions and credits associated with a 100 km trip in a car powered by electro-microbial isooctane, bioethanol or a rechargeable battery, each compared to a car powered by fossil gasoline. For example, the 2nd bar indicates that the use of bioethanol saves GHG emissions equivalent to 0.3 to 0.5 daily emission amounts of an average European citizen per 100 km transport.

* Impacts are normalised to daily inhabitant equivalents per 100 km transport.

In the best-case scenario, electro-microbial isooctane performs better than bioethanol and electric cars in the category 'climate change'. Regarding 'phosphate rock use', electric cars are superior to electro-microbial isooctane due to the high nutrient demand in the bioreactor. The phosphate rock footprints of bioethanol and electro-microbial fuels overlap. For a worst-case scenario, the environmental impact in the categories 'climate change' and 'phosphate rock use' of electro-microbial isooctane is considerably worse than for bioethanol or electric cars. On the other hand, the worst-case scenario results in land and water use comparable to the alternatives, especially in case of bioethanol. Scenarios involving energy sources other than renewable electricity are always worse than the alternatives.

The key results of the life cycle assessment can be summarised as follows differentiated in 3 subtopics:

- eForFuel vs. conventional fuels
- eForFuel vs. other renewable transport fuels and/or power-trains
- Optimisation potentials

Results: eForFuel vs. conventional fuels

The screening life cycle assessments carried out show that the electro-microbial fuels investigated can only under very specific conditions achieve energy and greenhouse gas balances that are better than those of conventional (fossil) fuels. These include:

- A pre-condition for climate change benefits is that the energy used for electricity and heat is associated with low CO_2 emissions, which is generally the case for electricity from renewable sources, especially from wind power. However, even when using 100% wind power, which is associated with very low environmental burdens but not entirely burden-free or CO_2-neutral, the enormously high electricity demand of currently foreseeable 280-495 kWh / 100 km mileage contributes significantly to all environmental impacts. In case of electricity and/or heat supply from non-renewable sources, additional GHG emissions would be caused.
- For a favourable GHG balance, however, it is not sufficient to use *any* renewable electricity. Rather, it depends on the CO_2 emission factor of the electricity used: depending on technology development, the break-even point can be as low as 30 g CO_2eq / kWh. Significant GHG emission savings can only be achieved at <15 g CO_2eq / kWh, currently only attainable with offshore wind power.
- Whether and to what extent advantages or disadvantages are achieved with regard to climate change is – in addition to the efficiency of the electroreactor and bioreactor – crucially dependent on the accounting of the co-product oxygen. If this is used and thus substitutes conventionally produced oxygen, e.g. from an air separation unit (ASU), a credit can be given in the LCA for the avoided environmental burden of the substituted product. However, the future development of the oxygen market is not foreseeable: in case of a massive expansion of water electrolysis (produces the co-products hydrogen and oxygen) in the course of an EU hydrogen strategy [European Commission 2020], a credit at the current level might no longer be justified. With a significantly lower credit, GHG emission savings would shrink significantly, so that the overall GHG balance may be unfavourable.

In addition, the aforementioned potential environmental benefits related to climate change and energy use are always associated with negative environmental impacts. Even in a best-case scenario (optimistic technology development and complete heat integration), there are i) disadvantages regarding the water and phosphate footprint and ii) no clear results regarding the other environmental impacts investigated. This applies equally to all three e-fuels that were investigated.

In the Renewable Energy Directive (RED II), the European Commission is required to adopt a delegated act establishing appropriate minimum thresholds for greenhouse gas emissions savings of recycled carbon fuels (RCF) as well as a delegated act on the GHG calculation methodology for renewable fuels of non-biological origin (RFNBO) and recycled carbon fuels (RCF). Since these two delegated acts were not yet available at the time of compiling this study, it was not possible to investigate whether the electro-microbial fuels considered comply with the minimum GHG emission savings set forth in the RED II.

Results: eForFuel vs. other renewable transport fuels and/or power-trains

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Another goal of the eForFuel project was to develop processes for the production of renewable hydrocarbon fuels that are more environmentally friendly than biofuels. In addition to the greenhouse gas balance, the environmental comparison focused on the land, phosphate and water footprints, since agriculture is by far one of the largest consumers of these resources and every effort should be made to use them sparingly.

The life cycle comparison between electro-microbial fuels and biofuels show that the e-fuels investigated certainly have the potential to perform similarly to biofuels in terms of climate change and even to show a better GHG balance. However, the latter is only applicable in a best-case scenario and with full oxygen credit. Under unfavourable conditions, the GHG balance (and also the phosphate footprint) of the e-fuels investigated can also be significantly worse. In the case of the land and water footprints in particular, the ranges overlap considerably, so that neither the electro-microbial fuels nor the biofuels show any genuine advantages over the others. Thus, from an environmental protection perspective, no clear preference in one direction or the other can be derived at present.

A third objective of the eForFuel project was to determine the environmental impact of alternatives to electro-microbial fuels that use the same resources: Renewable electricity for the production of electro-microbial fuels via electro- and bioreactors will remain a scarce resource for the foreseeable future, so the question of the most efficient use of the same inevitably arises. Instead of electro-microbial fuels (eForFuel concept), on the one hand, hydrocarbon fuels produced purely electrochemically (by means of water electrolysis and subsequent fuel synthesis) could also be used in an internal combustion engine vehicle (ICEV). On the other hand, renewable electricity could also be used directly in battery electric vehicles (BEV) with an alternative power-train.

Both alternatives show a significantly higher efficiency in electricity use of about 115 kWh / 100 km [BMU 2021; Liebich et al. 2021] and 15-20 kWh / 100 km [BMU 2021; Kämper et al. 2020], respectively, compared to the currently foreseeable 280-495 kWh / 100 km for the electro-microbial fuels investigated here. The life cycle comparisons between electro-microbial fuels and electric cars show that the latter have clear advantages in terms of land, phosphate and water footprint and are therefore preferable from an overall environmental perspective. Only in a best-case scenario could the GHG balance of electro-microbial fuels possibly be better. In road transport, electro-microbial fuels are thus facing strong competition. In air and maritime transport as well as in some specific parts of road transport, however, the direct use of renewable electricity is not possible or only possible to a very limited extent, so that niches for e-fuels could certainly form here. But even in these areas, purely electrochemically produced e-fuels would be superior to fuels produced via the eForFuel concept.

Results: Optimisation potentials

Even if the electro-microbial fuels investigated here do not offer any significant potential in the transport sector, further development may still be worthwhile – either to achieve significant increases in efficiency and/or to develop other product areas. Valuable insights were gained in this regard and optimisation potentials along the value chain were identified, of which the main ones lie in the electroreactor (including concepts for the high-quality use of oxygen, followed by the bioreactor [Rettenmaier et al. 2021].

Conclusions

Based on the key findings from the screening life cycle assessment, the following conclusions can be drawn:

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- Innovative e-fuels for transportation are not environmentally friendly *per se*, i.e. just because renewable resources are used for their production. Even if renewable resources are often associated with a low environmental burden, they are not entirely 'burden-free' or 'CO_2-neutral'. Therefore, if huge amounts (e.g. of renewable electricity) are used, even low *specific* emissions matter. The investigated electro-microbial fuels can only achieve GHG emission savings compared to conventional fuels if 100% renewable electricity (preferably wind) is used. The linchpin - besides the efficiency of the electro- and bioreactor - is the accounting of the co-product oxygen, which could be available in surplus in the future as a co-product of renewable hydrogen. Since the credit for conventionally produced oxygen could then be reduced or even completely lost, all optimisation potentials along the entire value chain must be fully tapped.
- Neither the electro-microbial fuels nor the biofuels have any genuine advantages over the others from an environmental point of view. Compared to electrochemically produced fuels, the efficiency of electro-microbial fuels would have to be increased by several factors in order for them to perform better, at least from a climate protection point of view. In the areas where battery electric cars can be used and operated with renewable electricity, they are clearly better. Therefore, prospects in the transport sector from an environmental protection point of view are only conceivable if the eForFuel concept is significantly improved.
- Like a number of other studies, the present study shows that e-fuels are not the silver bullet towards the defossilisation of the transport sector. The potentials of i) renewable electricity or areas for its expansion in Europe and ii) CO_2 from large point sources (of which, moreover, the fossil ones must disappear as far as possible for climate protection reasons) can at best replace a small part of today's fuel demand. With the eForFuel concept, a plant with a 1 GW electrolyser would need an amount of electricity equivalent to the annual production of a large conventional power plant (coal-fired or nuclear), but which would have to be provided from renewable sources. This would require an offshore wind farm with a surface area of 304-1,140 km² or a PV plant with 82-127 km². With the resulting fuel production of 82,000 tonnes/year, just 0.15% of German fuel consumption in road traffic could be covered. However, land area is a scarce resource in densely populated Europe. The same applies to marine areas suitable for offshore wind parks.
- LCA is a very versatile and suitable tool, not only to quantify environmental impacts of fuels, but also to identify hot spots and optimisation potentials to steer the development of electro-microbial fuels towards sustainability. It is important to analyse the entire life cycle and all environmental impacts. In terms of eForFuel, the main optimisation potentials lie in the electroreactor (including concepts for the high-quality use of oxygen), followed by the bioreactor.

5.2. Summary: techno-economic assessment

A techno-economic assessment (TEA) of the electro-microbial production of transport fuels according to the eForFuel concept was carried out, using a gas-flow-based simulation model to estimate the global economic performance [Peleman & Van der Stricht 2021]. The objective of TEA was to develop an initial business case for the eForFuel project based on a combination of mass & energy balances and estimated feedstock and processing costs.

For the analysis, a use case was determined for an industrial-scale installation defined by a blast furnace gas inflow of 5000 Nm^3/h, containing 26% CO_2. The business model was set up for the three routes producing propane, isooctane and isododecane (jet fuel) and optimistic, typical and conservative technology development, resulting in a total of 9 potential pathways. Sensitivity analyses were carried out with alternating gas flows and conversion rates of the steel gas to hydrocarbons. This use case roughly corresponds to the mass & energy flows underlying the 'typical' scenario investigated in the LCA and sLCA. For the 'optimistic' and 'conservative' scenarios, however, production volumes were kept constant in the TEA (and not varied as in the LCA and sLCA).

Results

The results for the base case simulation for each of the 9 considered pathways in terms of EBITDA (Earnings before interest, taxes, depreciation, and amortization) are given in Figure 13.

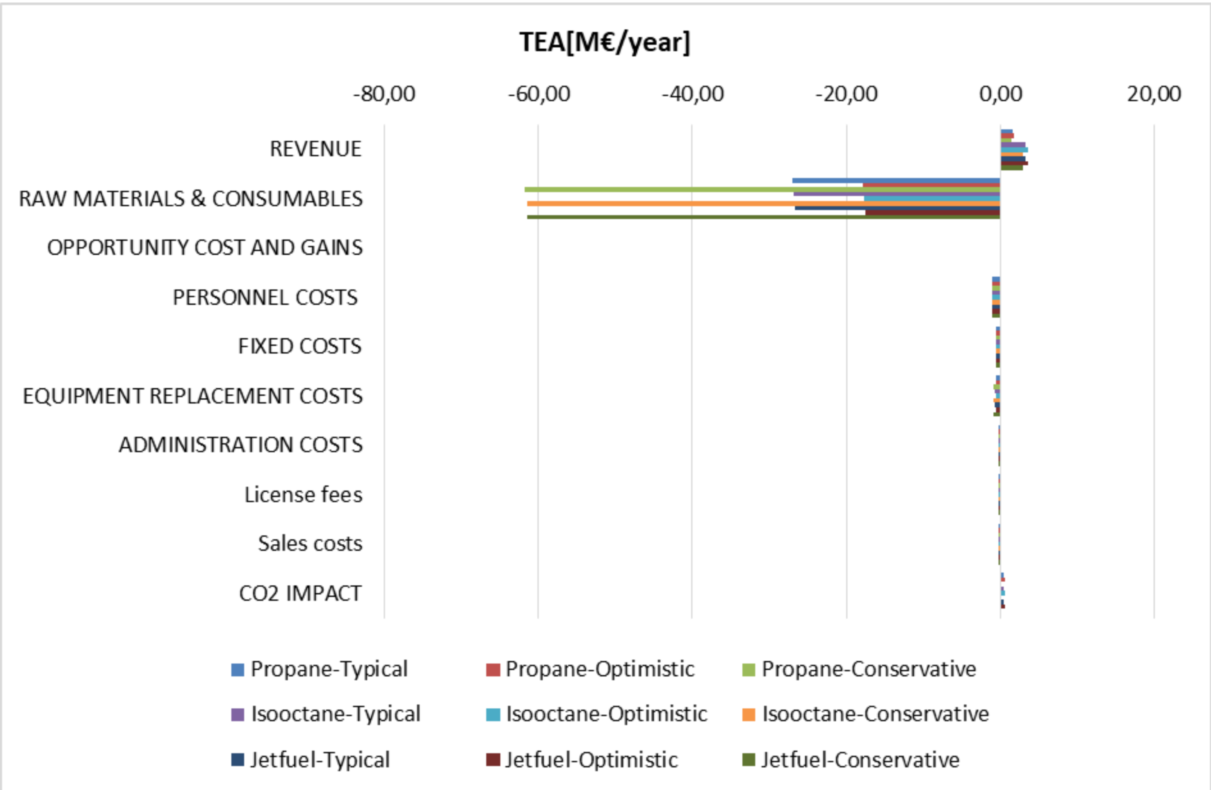

Figure 13: Simulated base case EBITDA results by contributing cost driver.

It can be seen that the overall impact is clearly dominated by the cost of the raw materials and consumables (negative) and the revenue on the products (positive). A closer look at the raw materials and consumables shows that the dominating cost driver is the electrical power consumption (Figure 14).

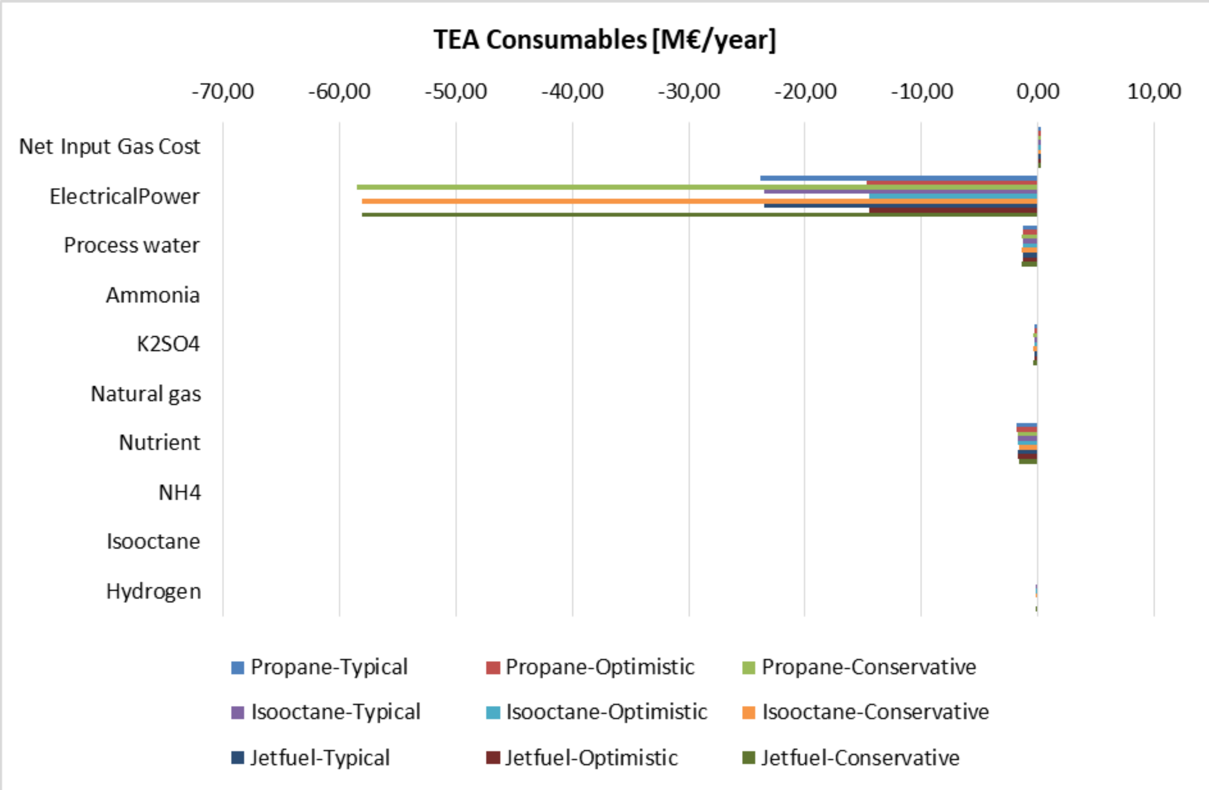

Figure 14: Simulated base case EBITDA results of raw materials.

Important for the optimization of the eForFuel concept is the fact that the negative EBITDA cannot be compensated solely by the electricity price alone. In the case of the typical scenario for propane production, a negative electricity price of -8.4 euros/MWh would be required to achieve cost-covering EBITDA, for example. Therefore, an improvement of other elements such as yields in combination with electricity price reductions is required.

Sensitivity analyses show that neither a plausible increase in the product selling price nor a rise in the CO_2 emission price have a decisive influence on the economic performance of the eForFuel concept. On the other hand, both an increase in the conversion yield and especially a reduced electricity price have an effect on a substantial increase in EBITDA.

Conclusions

Based on the analysis of the first simulated scenarios, the profitability of the process could not yet be demonstrated. Two main process parameters were shown to be dominating the total cost performance: product yield (positive impact on profitability) and the purchase of electrical power (negative impact). A sensitivity analysis revealed that a variation of power prices can have a bigger effect on estimated global EBITDA. To improve the profitability of the technology, both yield (conversion of CO_2 to formic acid) and electricity use would need to be improved significantly. Simulations indicate that the likelihood of reaching economic viability (break-even EBITDA) is very low even when taking into account the most optimistic estimates for the operating and pricing conditions.

5.3. Summary: socio-economic and policy assessment

A socio-economic and policy assessment was carried out for the electro-microbial production of transport fuels. The assessment consists of (i) a social life cycle assessment (sLCA) of the socio-economic impacts which the implementation of the eForFuel concept can have as well as (ii) an evaluation of potential social and policy barriers to the implementation of the eForFuel concept.

Results: Social impacts of eForFuel on society

Social life cycle assessment (sLCA) is based on the life cycle thinking approach like environmental LCA. For that reason, many provisions from international environmental LCA standards [ISO 2006a; b] and the common definitions and settings described in section 3.2 were are applied to the sLCA study, too. The methodology of the sLCA study follows the guidelines for social life cycle assessment of products and organizations [Benoît Norris et al. 2020]. For details and further results please refer to the original social and policy assessment report [Keller et al. 2021]. Social risks associated with different production stages of the electro-microbial fuel production were assessed for all social risks provided by the SHDB aggregated in 25 subcategories. These risks are contrasted with the avoided risks in order to put them into context. Figure 15 shows the risks displayed in work-hours needed for the production of 1 MJ transport fuel that are equivalent to work-hours at medium risk.

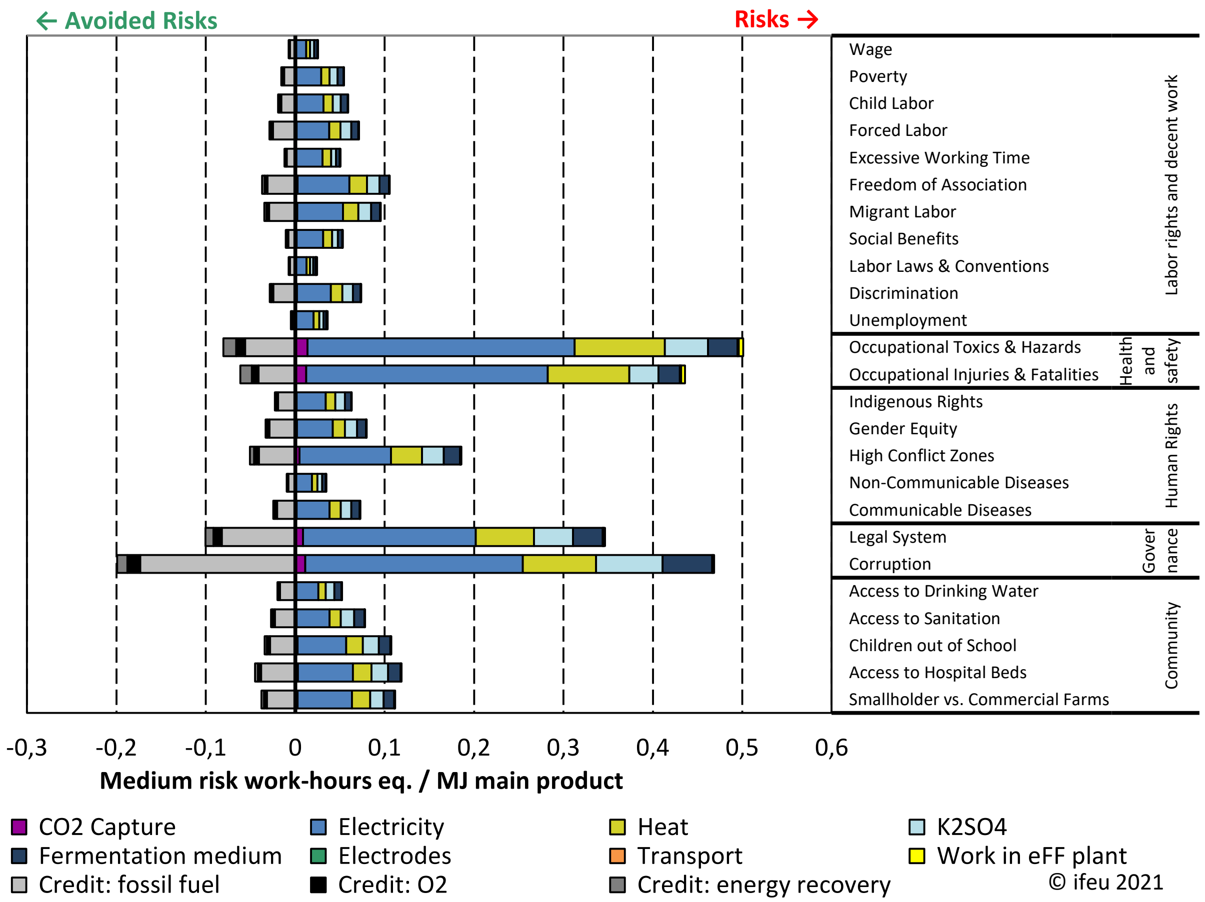

Figure 15: Overview of social risks and avoided risks at subcategory level of electro-microbial e-fuel in the baseline scenario*.

How to read the figure: Using the example of the social subcategory 'occupational toxics & hazards' belonging to the social category 'Health and safety': The bar sections on the right hand side illustrate that the production of isooctane in a process corresponding to the baseline scenario is associated with about 0.5 work-hour equivalents at medium risk in this subcategory per MJ main product. About 0.1 work-hour equivalents at medium risk can be avoided because conventional products and their production are replaced by eForFuel products.

* Transport fuel type: isooctane; technology development: typical; CO_2 source: blast furnace gas from steel plant; country: Belgium.

Figure 15 shows that the category 'Health and safety' comprising the subcategories 'Occupational toxics & hazards' and 'Occupational injuries & fatalities' as well as the category 'Governance' comprising the subcategories 'Legal system' and 'Corruption' dominate the social risks. Slightly less social risk but still pronouncedly more than for other subcategories is expected for the subcategory 'High conflict zones'. Having a look at the process stage level, electricity and heat contribute most to all social subcategories. Electricity and heat are followed by the electrolyte K_2SO_4 of which a large amount is needed due to its low recovery rate and the low overall efficiency of the process. Furthermore, the fermentation media contributes significantly to the social risks. In contrast, the contribution of the electrodes, although containing potentially problematic metals (iridium, tin) typically procured from countries with high social risks, is negligible. This is due to the small amount used in the scenario considered. Similarly, risks from transport and the work in the eForFuel plant are low. Although the analysed location of the plant and of its direct (tier 1) suppliers is Belgium, more than 80% of the work hours at risk are done at higher tier suppliers outside of Belgium and mostly outside of the EU.

Results: Social and policy barriers to implementation

Besides assessing the potential impacts of a future implementation of the eForFuel concept on society (see sub-section above), this sub-section shows potential impacts of society on a future implementation of the eForFuel concept from the opposite, i.e. social and policy barriers to implementation. This includes public perception, market acceptance as well as the regulatory framework and policies. For the evaluation of public perception a survey has been conducted, which examined how recycling of industrial CO_2 emissions into drop-in fuels (so-called recycled carbon fuels, RCF) would be perceived by European citizens [Schmidt & Youssef 2020]. The survey was performed in the form of 6 citizen engagement activities across Europe (Portugal, Denmark, the Netherlands, Estonia, Spain & Italy) involving 165 participants. The events were divided into three sections: (i) fossil fuels, CO_2 and carbon capture, (ii) project ambitions and possible applications and (iii) economic dimensions, subsidies and energy sources. The survey design included multiple- and single-choice questions as well as qualitative reflection questions.

Regarding potential target products of the eForFuel concept, the participants showed a cautiously positive view on most product categories (except for animal feed, which was viewed rather negatively), with a slight preference for aviation fuel. Around two thirds of the participants had a neutral to positive opinion regarding the use of GMO, but with comments towards biosafety and biosecurity. Figure 16 shows that recycled carbon fuels (RCF) were rated more favourable than fossil fuels but less favourable than fuels from renewable sources (so-called renewable fuels of non-biological origin, RFNBO). Most participating citizens were favourably inclined to the eForFuel concept and the recycling of industrial CO_2 emissions into drop-in fuels. However, there were some reservations about using this CO_2 source which was considered a treatment of symptoms rather than curing the cause of the problem (increase of atmospheric CO_2 concentrations), e.g. by a systemic change. Nevertheless, since the topic is of high relevance to citizens, the majority was in favour of the technology, but it was seen as one of many possible measures rather than as the silver bullet.

As opposed to fuels from recycled carbon (RCF), fuels from renewable sources (RFNBO) were seen much more favourable. It has to be noted that the survey on public perception did not catch a representative sample of the European population. Admittedly, this was not the aim of the surveys, but must be taken into account when interpreting the results[2].

In the eForFuel project, a preliminary market exploration of eForFuel target markets has been conducted by [Candotti et al. 2021], including the markets of CO_2, formic acid, e-fuels as well as (bio-)isooctane/iso-dodecane and (bio-)propane. The assessment showed that e-fuels generally have a chance of a positive market acceptance. On one hand, the fuel market is huge, but on the other hand, fuels are considered low added-value, high volume products. At the end of the day, the costs of the electro-microbial fuels will determine their market acceptance. Moreover, the transport sector will have to undergo a massive transformation and therefore, those subsectors in which greenhouse gas emissions are hard to abate (e.g. aviation) should be targeted primarily.

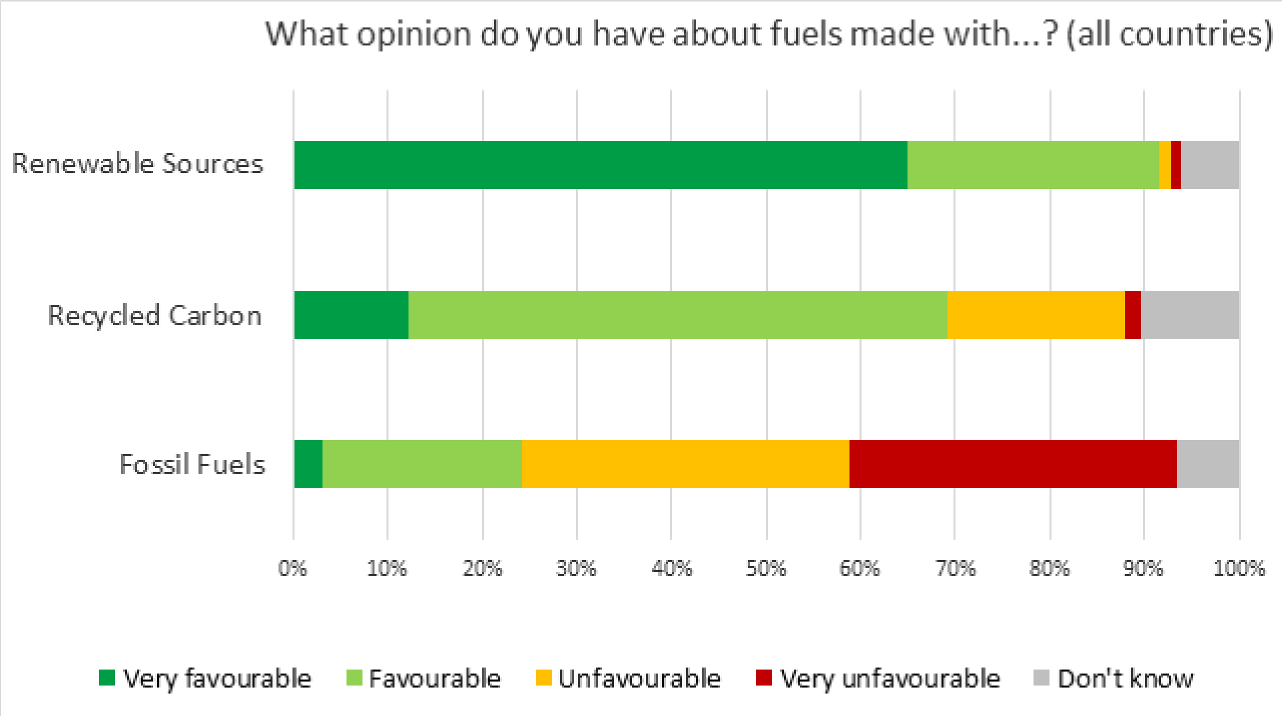

Figure 16: Evaluation of the production of fuels from renewable sources (RFNBO), recycled carbon (RCF) and fossil fuels across all six countries [Schmidt & Youssef 2020]

[2] A recently published media analysis on CO_2 utilisation technologies by [Olfe-Kräutlein 2021] concluded that in German-language media, positive aspects of CCU technologies are reported significantly more often than negative aspects. The technology area 'fuels' experiences the greatest media interest and especially advantages from a climate protection perspective are mentioned disproportionately more frequently. Since media have a significant influence on the perception of certain topics [Bonfadelli & Friemel 2017], this may be an indication of the tendency towards positive public perception of CCU concepts such as eForFuel. Note: the mentioned media analysis was neither part of the socio-economic and policy assessment nor of the integrated life cycle sustainability assessment.

Another barrier for the implementation of the eForFuel concept could be the regulatory framework and policies, studied by [Parco & Rettenmaier 2020]. In terms of the regulatory framework, Directive (EU) 2018/2001, the so-called Renewable Energy Directive or RED II, has been identified as most important, since it specifies the conditions under which certain types of renewable fuels are eligible to count towards the renewable energy targets set therein [European Parliament & Council of the European Union 2018]. Notably, a number of open issues related to Articles 25, 27 and 28 of the RED II might affect the short- and medium-term market deployment of eForFuel products. For instance, the minimum threshold for GHG emission savings of recycled carbon fuels (RCF) needs to be set (Article 25). Furthermore, eligibility criteria for the sources of electricity (renewability, temporal correlation, geographical correlation and additionality) have to be defined (Article 27) and the calculation methodology for determining the greenhouse gas impact of RFNBO and RCF has to be agreed upon (Article 28). In order to clarify these issues, the European Commission was requested to adopt a series of delegated acts in 2021. These were expected in the fourth quarter 2021 [European Commission 2021a; b; c], but at the time of compiling this report, they were still pending.

Conclusions

The results of the social life cycle assessment show that the social risks associated with electro-microbial fuels according to the eForFuel concept vary within a wide range because, amongst other reasons, efficiencies of potential mature, industrial scale process are very uncertain. This is also reflected in large differences between electricity and other inputs required, as modelled for scenarios under optimistic, typical and conservative boundary conditions. A comparison of e-fuels to replaced fossil fuels in terms of social risks is challenging because future socio-economic structures and related risks of very large scale renewable electricity provision are still unclear to a large extent. If risks should be comparable to those in the current fossil-dominated electricity sector, then electro-microbial fuels according to the eForFuel concept would be associated with similar to much higher overall social risks compared to fossil fuels. This is however rather due to the high amounts of inputs required than due to high specific risks for the inputs.

Most risks occur in the areas of occupational health and safety as well as governance (corruption, legal system etc.) and largely originate from parts of the supply chain outside of the EU, often at indirect (higher tier) suppliers. Work in the eForFuel installation itself is only connected to low risks. A socially beneficial implementation of these electro-microbial fuels would therefore require (i) technical improvements to reach efficiencies towards the upper end of the modelled range and thus lower demands of inputs as well as (ii) a careful monitoring and management of social risks in the supply chain. The latter should focus on the following hot spots:

- The most important social risks are connected to the provision of the very high amounts of electricity needed for the production of e-fuels. Although specific social risks associated with renewable electricity cannot be deduced yet from the most recent available social risk databases, it is expected that electricity provision will remain a social hot spot in the life cycle of e-fuels for decades.
- The enormous amounts of additional renewable electricity generation capacity required to be built up globally in the next decades will bring many socio-economic challenges and chances. This developing market needs to be further analysed, monitored and managed by all involved actors, including industry and politics. Risks are particularly high in countries with less developed public health, social welfare and governance systems. If substantial electricity imports into the EU, e.g. from the Middle East and North Africa (MENA region), are considered for e-fuels, it must be ensured that suppliers not complying with social standards are excluded – despite dependencies that may have evolved and higher costs elsewhere.

- Other social hotspots are related to the provision of the electrolyte K_2SO_4 and fermentation media. Also for these inputs, most social risks originate from parts of the supply chain outside of the EU, often at indirect (higher tier) suppliers. Suppliers should be selected from the established market according to social reporting standards such as those of the Global Reporting Initiative (GRI), also covering their suppliers.


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Social risks created by the emerging large-scale renewable electricity production, which is crucial for the assessed e-fuels, cannot be determined by sLCA and have been covered by a literature study. Direct impacts are mainly determined by the way of implementation and can be overall very positive if just and inclusive processes are followed and burdens and benefits are shared in a fair way. Not following these principles increases the risk of sometimes fierce resistance against new renewable electricity installations. Indirect risks in the supply chain of providing resources such as cobalt for wind turbines can be critical and have to be managed.

As for renewable electricity provision, the overall social impacts of producing e-fuels can be positive, too, despite all risks identified by the sLCA methodology. As most important positive social impacts, installations producing e-fuels according to the eForFuel concept can provide some jobs in the installation itself and many more in the supplying industries. Furthermore, replacing particularly (food and feed) crop-based biofuels could in tendency lead to a mitigation of social risks in fuel supply chains but efficiencies in the production of electro-microbial fuels have to be highly optimised not to cause similar risks elsewhere.

The analysis of potential social and policy barriers has revealed a number of issues that could potentially act as obstacles for the deployment of the eForFuel concept. The following can be concluded:

- Based on the public perception survey conducted by [Schmidt & Youssef 2020], no final conclusions can be drawn whether public perception is a potential barrier to the implementation of the eForFuel concept. Currently, this does not seem to be the case but future developments are unpredictable.
- Due to the low public knowledge about CO_2-based technologies, CCU (Carbon Capture and Utilisation) and CCS (Carbon Capture and Storage) are often confused in the public discourse. Given earlier experiences with the public perception of CCS, there could be the risk that stakeholders critical towards CCS could directly transfer their critical attitude onto CCU.
- In view of heated debates in the media on the role of e-fuels, it seems to be of utmost importance for eForFuel to carefully think about a communication strategy which highlights the strengths of the concept but avoids any greenwashing.
- Market acceptance of the assessed e-fuels seems to be determined mainly by price and technical compatibility, in particular for jet fuels. Market size is not limiting in the foreseeable future but targeting in particular the markets of marine and aviation fuels, which are hardest to replace by direct electrification, with priority seems reasonable.
- The most significant barriers to implementation result from the legal uncertainty, which is due to an absence of legislation in the context of the Renewable Energy Directive (RED II). A number of open issues related to Articles 25, 27 and 28 of the RED II might affect the short- and medium-term market deployment of eForFuel products. However, the adoption of the long-awaited corresponding Delegated Acts by the European Commission was planned for the fourth quarter 2021.

- In this context, it remains to be seen whether another potential barrier related to the regulatory framework will be resolved: the interplay between the EU ETS Directive (Directive 2003/87/EC) and the RED II. This concerns a potential accounting loophole for fossil CO_2 emissions which could lead to neither counting these in delivering sectors such as steel and concrete plants nor in the receiving fuel sector. In case this loophole is not plugged in the sense of avoiding a double omission of CO_2 emissions, this could severely damage the public perception of CCU technologies.
- Last but not least, we have to acknowledge that while still waiting for important bits and pieces of the regulatory framework which is currently in force, new proposals for significant amendments and changes to the latter are already on the table. It remains to be seen which of these proposals survive the upcoming legislative procedure, but it is clear that this transition period does not provide a stable investment climate and rather prevents engagement in large-scale e-fuel projects in the EU.

Taken together, social impacts and barriers to implementation are not direct physical consequences of processes. They can be influenced to a very large extent by socio-economic implementation strategies. Nevertheless, also technical optimisation, in particular increasing the efficiency in electricity use, is needed to improve the balance of benefits and risks. The social risks identified in this study are no reason to refrain from implementation but rather entail obligations. They should be taken as starting points to design a strategy of monitoring and mitigating risks. In particular e-fuel producers and policy makers should use the chances to develop an emerging international market for renewable electricity and derived products to the benefit of all stakeholders.

6. Results: Integrated sustainability assessment and SWOT analysis

The integrated sustainability assessment builds on the results of three separate assessments of individual sustainability aspects whose results are summarised in sections 5.1 - 5.3. This chapter combines, extends and jointly assesses these individual results in order to give an integrated view on the sustainability impacts of the eForFuel value chains. For methodological details, definitions and settings, see chapter 3.

First, an overview of sustainability impacts of all analysed value chains is provided in section 6.1. Second, a SWOT analysis of the assessed sustainability impacts (section 6.1) is performed in order to derive key findings of the integrated sustainability assessment (section 6.2). Finally, an overall comparison of the sustainability aspects of the eForFuel concept will be conducted (section 6.3)

6.1. Overview of implications for sustainability

Selection of scenarios and indicators

As described in chapter 4, twelve scenarios were selected for the integrated sustainability assessment in an early phase of the eForFuel project [Rettenmaier et al. 2019], which were subsequently subjected to individual analyses of their impacts on the environment, the economy and society.

Various environmental, economic, social and political aspects relevant for sustainability have been studied in individual assessments, which form the basis of this integrated sustainability assessment (for summaries see sections 5.1 - 5.3). The performance of the investigated eForFuel scenarios and conventional reference systems regarding all these aspects is quantified or qualitatively rated using various indicators.

The indicators include sustainability indicators in the strict sense, which depict impacts on objects of protection such as climate or human health. Further indicators depict barriers that may prevent the implementation of the scenario. Such barriers may lead to substantially worse actual sustainability impacts when trying to implement a scenario, for which low potential impacts were anticipated. Another type of indicators reflects risks that may lead to substantially worse sustainability impacts in case of accidents etc. This is needed because scenarios are only assessed under routine operation conditions, thus excluding such rare incidents by definition. The suitability and scientific validity of the indicators has been verified in the individual assessments.

For the integrated sustainability assessment, the indicators of the life cycle assessment (LCA) and the techno-economic assessment (TEA) were adopted directly. In the TEA, a use case was defined which roughly corresponds to the mass & energy flows underlying the 'typical' scenario investigated in the LCA (and sLCA). For the optimistic and conservative scenarios, however, the production volumes were kept constant in the TEA (and not varied as in the LCA and sLCA). Thus, for the integrated sustainability assessment, the results of the optimistic and conservative scenarios had to be scaled according to the input parameters used in the other assessments.

Regarding the socio-economic and political aspects of sustainability, the 25 social indicators of the sLCA were grouped into the 5 quantitative impact categories ('labour rights and decent work', 'human rights', 'health and safety', 'governance' and 'community') provided by the social hotspot database (SHDB) [Benoît Norris et al. 2019] to consider possible social risks. In contrast to environmental and economic impacts analysed in LCA and TEA, a comparison of aggregated sLCA results with those of reference systems cannot yield similarly robust conclusions for a variety of reasons including robustness of input data. Additionally, social impacts of renewable energy provision, which are crucial for the assessed scenarios, can only be fully assessed in hindsight once social structures have developed in the emerging European and international market for large scale renewable electricity. Therefore, disadvantages in sLCA results are not necessarily a reason to refrain from implementation but rather entail obligations for risk management. Next to the aforementioned sLCA-based indicators, the indicator 'public perception' was introduced, which interprets the results of the public perception survey [Schmidt & Youssef 2020] in a qualitative manner.

For an overview and a short description of all indicators assessed see Table 3.

Table 3: Overview of sustainability indicators selected for the integrated assessment.

Impact category	Short description
Environment	
Non-renewable energy use	Depletion of non-renewable energy resources, i.e. fossil fuels such as crude oil, natural gas, coal and uranium ore.
Climate change	Climate change as a consequence of the anthropogenic release of greenhouse gases.
Acidification	Shift of the acid/base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword 'acid rain').
Eutrophication, terrestrial	Input of excess nutrients into terrestrial ecosystems via gaseous emissions of different nitrogen species such as ammonia and nitrogen oxides
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword 'ozone hole').
Particulate matter	Damage to human health due to air pollutants from routine operation such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, keyword 'London smog').
Phosphate rock use	Depletion of the limited phosphate resources and contribution to increasing scarcity [Reinhardt et al. 2019].
Land use	Occupation of land at varying degrees of human influence on a natural area [Fehrenbach et al. 2015, 2019].
Water use	Depletion of freshwater resource from surface and groundwater bodies ('blue' water'), qualified according to the scarcity in the respective watershed [Boulay et al. 2018].
Economy	
EBITDA	'Earnings before interest, taxes, depreciation, and amortisation' is a measure of a company's profitability of the operating business only, i.e. it excludes expenses associated with debt, decline in asset value and obligations to governments.
Society & Policy	
Labour rights & decent work	Risk of unfair conditions of work or labour accords violations in the value chain; such as child labour, low wages, forced labour, excessive working time or suppression of workers association.
Health & safety	Risk along the value chain of high prevalence of occupational injuries and deaths, as well as high exposure to workplace hazards.
Human rights	Risk of human right violations along the value chain; such as infringements of indigenous rights, weakness of gender equality, potential for high conflicts and prevalence of diseases.
Governance	Risk of manufacturing processes located in countries or regions with weak legal systems, with high risk of corruption or poor law enforcement.
Community	Risk of negative impacts along the value chain to the local community; such as school for children, drinking water, sanitation, hospital beds and land ownership of small land holdings.
Public perception	Public perception on recycling industrial CO_2 emissions into different drop-in fuels

Overview of results

Table 4 shows an overview of all sustainability impacts of the investigated eForFuel scenarios. While the result values are derived from the respective reports [Rettenmaier et al. 2021; Peleman & Van der Stricht 2021; Keller et al. 2021], an assessment was carried out within the framework of the ILCSA on the basis of qualitative or significant quantitative differences and marked using a traffic light colour system (for details on the methodology, see section 3.3.2).

Table 4: Overview of results for life cycle comparisons of eForFuel scenarios to their conventional / fossil alternatives for conservative, typical and optimistic sub-scenarios.

			eForFuel scenarios					
			Conservative					
			1	2	3	10	11	12
	Indicator	Unit	Propane vs. LPG, PV (Munich)	Isooctane vs. gasoline, PV (M)	Isododecane vs. jet fuel, PV (M)	Isooctane vs. 1G EtOH, PV (M)	Isooctane vs. 2G EtOH, PV (M)	Isododecane vs. FT biojet, PV (M)
Environment	Non-renewable energy use	MJ cumul. primary energy / GJ	4467	5006	5231	6038	5974	5183
	Climate change	kg CO_2 equivalents / GJ	333	365	389	427	418	443
	Acidification	g SO_2 equivalents / GJ	2909	3182	3388	2825	2860	2989
	Eutrophication, terrestrial	g PO_4 equivalents / GJ	139	148	162	76	94	113
	Ozone depletion	g CFC-11 equivalents / GJ	0.17	0.19	0.20	-0.64	-0.95	0.14
	Particulate matter	g PM2.5 equivalents / GJ	2136	2344	2499	1959	2091	2091
	Phosphate rock use	g phosphate rock std. / GJ	8093	8924	9433	7812	5371	7269
	Land use	$m^2 \times yr$ artificial land equivalents / GJ	52	57	60	26	57	59
	Water use	m^3 water equivalents / GJ	5.5	6.1	6.4	4.8	2.8	6.2
Economy	EBITDA	Euro / GJ	-418	-431	-431	-431	-431	-431
Society & Policy	Labor rights & decent work	Mrh / GJ	1740	1901	2062	N/D	N/D	N/D
	Health & safety	Mrh / GJ	2943	3230	3436	N/D	N/D	N/D
	Human rights	Mrh / GJ	1145	1253	1362	N/D	N/D	N/D
	Governance	Mrh / GJ	2132	2328	2543	N/D	N/D	N/D
	Community	Mrh / GJ	1184	1294	1413	N/D	N/D	N/D
	Public perception	qualitative	o	o	+	N/D	N/D	N/D

Table 4: (continued).

eForFuel scenarios																
Typical										Optimistic						
13	14	14b	14c	15	17	20	22	23	24	25	26	26b	27	34	35	36
Propane vs. LPG	Isooctane vs. gasoline	without credit O_2	PV (Munich)	Isododecane vs. jet fuel	Isooctane vs. gasoline, CO_2 DAC	Isooctane vs. gasoline, CO_2 DAC	Isooctane vs. 1G EtOH	Isooctane vs. 2G EtOH	Isododecane vs. FT biojet	Propane vs. LPG	Isooctane vs. gasoline	without credit O_2	Isododecane vs. jet fuel	Isooctane vs. 1G EtOH	Isooctane vs. 2G EtOH	Isododecane vs. FT biojet
-1852	-1934	207	305	-2038	-1900	-1973	-902	-966	-1322	-1918	-1963	-215	-2076	-931	-995	-1360
-142	-157	5	17	-157	-154	-159	-95	-103	-103	-143	-155	-23	-156	-93	-101	-102
-75	-122	578	879	-101	-102	-136	-479	-444	-501	-149	-198	373	-180	-555	-520	-580
-16	-23	26	30	-18	-21	-24	-95	-54	-163	-19	-25	14	-20	-97	-54	-221
-0.06	-0.06	0.03	0.01	-0.06	-0.06	-0.06	-0.89	-1.20	-115	-0.06	-0.06	0.01	-0.06	-0.89	-1.20	-172
-101	-132	439	623	-115	-116	-143	-517	-385	-524	-156	-187	279	-172	-573	-441	-581
1274	1328	1333	4083	1359	1334	1325	215	-2226	-805	1125	1149	1153	1183	36	-2404	-982
2	2	3	22	2	2	2	-29	2	0	1	1	3	1	-30	2	0
0.9	1.0	2.0	2.4	1.0	1.0	1.0	-0.3	-2.3	0.8	0.6	0.6	1.4	0.6	-0.7	-2.7	0.4
-153	-152	N/D	-152	-153	N/D	N/D	-152	-152	-153	-88	-84	N/D	-84	-84	-84	-84
430	440	N/D	440	507	453	425	-284	-258	-211	107	91	N/D	153	N/D	N/D	N/D
750	795	N/D	795	845	816	769	477	155	204	227	227	N/D	266	N/D	N/D	N/D
287	294	N/D	294	339	303	284	-269	-132	-102	72	61	N/D	104	N/D	N/D	N/D
509	515	N/D	515	612	531	495	-434	-180	-126	102	74	N/D	166	N/D	N/D	N/D
298	302	N/D	302	355	311	291	-444	-276	-238	74	59	N/D	110	N/D	N/D	N/D
o	o	N/D	o	+	+	+	N/D	N/D	N/D	o	o	N/D	+	N/D	N/D	N/D

6.2. SWOT analysis

A SWOT analysis of the assessed sustainability impacts (section 6.1) is performed in order to derive key findings of the integrated sustainability assessment. The results of the SWOT analysis are shown in Table 5.

Table 5: Results of the analysis of strengths, weaknesses, opportunities and threats (SWOT) of the eForFuel concept based on the individual sustainability indicator values.

	Helpful	Harmful
Internal origin	**STRENGTHS** • By using renewable electricity with a very low carbon intensity (e.g. offshore wind), a favourable GHG balance can be achieved. • Under (close to) optimistic boundary conditions, electro-microbial fuels show environmental and social advantages over biofuels. • Good conduct in high risk procurement of renewable energy can lead to social benefits in terms of decent work and additional income. • E-fuels may be the first choice for niche applications where direct use of renewable electricity is not possible, e. g. air and marine transport.	**WEAKNESSES** • Advantages from a climate perspective can only be achieved under close to optimal conditions. • Disadvantages regarding water and phosphate footprint as well as social impacts (esp. health & safety and governance) can be expected. • Socio-economic challenges due to enormously high renewable electricity demand: even under the most optimistic boundary conditions, social benefits are not guaranteed. • Given the (technical) conditions, economic production of electro-microbial fuels is not feasible. • Assuming conservative boundary conditions there will be disadvantages in all sustainability aspects assessed.
External origin	**OPPORTUNITIES** • The concept offers social opportunities for energy and power-supplying countries from North Africa and the Middle East, for example, through the development of new economic sectors and increasing energy sovereignty. It is important to build sustainable supply chains at eye level for the benefit of all stakeholders involved.	**THREATS** • Absence of legislation (RED II) may affect market deployment delay investment decisions. • Cost-efficient, direct use of renewable electricity in battery electric vehicles poses major competition. • Possible expansion of water electrol-ysis due to the EU hydrogen strategy could significantly lower the credit given for the co-produced oxygen → unfavourable overall GHG balance.

6.3. Overall comparison

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The following results can be derived from the collected results of the individual sustainability assessments, presented in Table 4 and the SWOT analysis (Table 5):

General results: Independent of the scenario-specific results, several general results can be indicated for the production of synthetic fuels according to the eForFuel concept: under close to optimistic boundary conditions, all scenarios show both advantages and disadvantages compared to a situation without eForFuel from an integrated sustainability point of view. This result is obvious at first sight through the coloured illustration in Table 4: both orange/red and green result boxes are included in each scenario column.

- Having a look at the environmental impacts of the eForFuel scenarios using offshore wind power as source of electricity (scenarios 13-15), net advantages are obtained in the impact categories 'non-renewable energy use' and 'climate change'. For phosphate rock use, however, electro-microbial fuels show disadvantages compared to fossil fuels in all cases, even under optimistic boundary conditions (scenarios 25-27). Moreover, electro-microbial fuels perform worse with regard to the water footprint. For the other environmental impact categories, electro-microbial fuels achieve comparable results than fossil fuels. Despite the fact that the main scenarios (scenarios 13-15) are close to optimal boundary conditions, they show disadvantages with regard to social aspects compared to the fossil reference fuels due to the large amount of electricity needed.
- Even under most optimistic conditions there are no advantages from a social perspective (scenarios 25-27). Dominating subjects are 'Health and safety' and 'Governance' and above all the sub-categories 'Occupational Toxics & Hazards', 'Corruption', 'Injuries & Fatalities', 'Legal system' and 'High conflict zones'.
- Nevertheless, the synthetic fuels considered in the eForFuel concept show a neutral to positive public perception. In general, jet fuels are slightly favoured.
- Due to the enormous amount of electricity needed for the production of electro-microbial fuels, none of the eForFuel scenarios is economically viable without financial support, even under optimistic boundary conditions. Under conservative boundary conditions using PV electricity with a slightly higher CO_2 emission factor, no advantages can be achieved over the fossil reference fuels from an environmental, economic or social point of view.

Electricity source: Greenhouse gas emissions associated with the production of e-fuels are highly dependent on the electricity source. While the use of electricity from offshore wind plants leads to clear advantages in terms of non-renewable energy use and climate change (scenarios 13-15), the use of central European PV electricity (with worse CO_2 emission factor) already causes slight disadvantages in these impact categories (scenario 14c). Thus, the CO_2 emission factor of the electricity used determines whether an overall favourable GHG balance can be achieved. Significant GHG emission savings can only be achieved at <15 g CO_2eq / kWh, which can currently only be realised with offshore wind power. In the future, by increasing efficiency and further technological progress, PV power from sunny regions of the world (e.g. Northern Africa) could also lead to a favourable GHG balance. The use of renewable electricity from countries that can produce PV power with a low CO_2 emission factor tends to be accompanied with higher social risks. Conversely, installations producing e-fuels according to the eForFuel concept can provide some jobs in the supplying industries and lead to a mitigation of social risks in fuel supply chains. Good conduct in high risk procurement can lead to great social benefits in terms of decent work and additional income. Thus, if sustainable supply chains are established and social aspects are adequately considered, benefits from a climate and social perspective can be achieved together.

Fuel type: The three electro-microbial fuels considered perform comparably in all the impact categories assessed. There are no advantages or disadvantages for any of the fuels investigated. It should be noted that public perception is slightly better for jet fuels.

CO_2 source: From both an environmental and a social point of view, there are no significant differences between the use of CO_2 from a steel mill, CO_2 from direct air capture (DAC) and biogenic CO_2 (scenarios 14, 17 and 20). The calculated values indicate that the use of CO_2 from steel mills tends to be slightly more advantageous than biogenic CO_2, but this is only expressed in the second decimal digit.

Credit for oxygen from electroreactor: Without a credit for O_2, the production and use of electro-microbial fuels shows no clear advantages over fossil fuels (scenarios 14b and 26b). Even under optimistic conditions, without any O_2 credit, electro-microbial fuels will no longer have climate and energy use benefits compared to fossil fuels. Thus, the rational use of the co-product oxygen plays an essential role with regard to the overall sustainability of the investigated fuels.

Comparison to biofuels: Under typical and optimistic boundary conditions, electro-microbial fuels perform better than biofuels from an environmental and social perspective (scenarios 22-24 and 34-36). However, under conservative boundary conditions, the tide is turning towards advantages for biofuels (scenarios 10-12), which is why no clear statement can be made for one fuel type or the other. Compared to 1st generation biofuels, social benefits are greater, while compared to 2nd generation biofuels, environmental benefits are more significant.

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Possible advantages of electro-microbial fuels compared to biofuels can be particularly pronounced for aviation fuels. In this case, there are also advantages with regard to other environmental indicators such as acidification, eutrophication, ozone depletion and particulate matter as well as social indicators (especially labour rights & decent work and community).

Based on Table 4, it could be shown that qualitatively significant differences from a sustainability perspective are caused by variations in the electricity source used, the credit for the co-product oxygen and the conventional reference product. It was confirmed that due to the moderate number of analysed scenarios, all major differences between the scenarios could already be derived from the overview table. This justifies the decision not to use the benchmarking step.

7. Conclusions and recommendations

The aim of this study is to provide an integrated view on the sustainability impacts associated with the production and use of electro-microbial fuels using CO_2 and renewable electricity. The main objective of this sustainability assessment was to determine whether or under which conditions the eForFuel concept can contribute to a more sustainable supply of transportation fuels for passenger cars and aviation. Another important goal was to identify optimisation potentials from to determine focal areas for the further development of the eForFuel concept. Based on the results in chapters 5 and 6, the following conclusions and recommendations were derived.

7.1. Conclusions

Based on the results of the specific assessments (chapter 5) and the results of the integrated sustainability assessment (chapter 6), the following conclusions can be drawn:

- Under the technical boundary conditions assumed, none of the eForFuel scenarios considered in the sustainability assessment proves to be economically viable. In terms of environmental impact, advantages **compared to conventional fossil fuels** can be achieved under ideal conditions - however, two preconditions must be met: (i) the emission factor of the electricity used must be very low (<15 g CO_2eq / kWh) and (ii) for the co-product oxygen, a credit must be obtained for (the avoided environmental impacts of) the replaced conventional oxygen. Furthermore, the eForFuel scenarios are associated with high social risks, which may even exceed the social risks associated with fossil fuels. However, this can only be reasonably assessed once social structures in the emerging European and international market have been established on a large scale.
- The enormously high specific electricity demand of the eForFuel concept, associated with high costs, social risks and environmental effects, has a very negative impact on the performance in all sustainability dimensions. Even though renewable resources often have a low environmental burden, they are not entirely 'burden-free' or 'CO_2-neutral'.
- **Compared to biofuels**, under the rather optimistic boundary conditions of the typical scenarios, slight advantages for electro-microbial fuels are apparent for some indicators from the dimensions of environment and society - as long as the above-mentioned criteria regarding the emission factor for electricity and the oxygen credit are met. However, even in these cases, advantages are not achieved in all scenarios and across all indicators. For example, in the case of the indicator 'Land use', advantages are only achieved compared to 1G ethanol.
- If technical breakthroughs in the electroreactor and the bioreactor can (i) significantly reduce the enormously high specific electricity demand and (ii) improve the internal recycling of gases, electrolyte and water substantially, the eForFuel concept could unfold its potential and offer a renewable alternative to conventional, fossil or even conventional as well as advanced biofuels.

- It remains to be seen to what extent it will be possible to keep up with other, purely electrochemically generated e-fuels (for road, air and marine transport) or battery electric vehicles (only for road transport) in terms of sustainability performance. Under the currently assumed technical boundary conditions, the competitors would clearly be ahead - at least from an environmental point of view. Ultimately, it will be the price that decides whether electro-microbial fuels can assert themselves on the fuel market.
- In order to enter the fuel market, a number of regulatory sustainability requirements of the Renewable Energy Directive (RED II) have to be fulfilled. The lack of some important delegated acts within the context of RED II currently represents the greatest uncertainty for the eForFuel concept. This has a negative impact on the further technical development and possible later market launch: the fulfilment of the minimum GHG emission savings could not be verified, as both the calculation principles and the threshold value for Recycled Carbon Fuels (RCF) are missing.
- The investigated concept of electrochemical CO_2 activation via reduction to formic acid, followed by microbial conversion to hydrocarbons, could possibly unfold its potential in other markets, where the strengths of fermentation in the flexible production of more complex and more highly oxidised molecules can be exploited better. Thus, it is conceivable to also address the area of classic bio-based products or even the food & feed market via proteins, for example.


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In summary, it can be concluded that from an overall sustainability point of view, the enormously high electricity demand and the low overall efficiency are the dominant factors with regard to the constrained sustainability performance of the eForFuel concept. Technical improvements achieving efficiencies at the upper end of the modelled range (or ideally beyond) would thus be imperative for reaching a sustainable production of electro-microbial fuels. If these technical improvements are accompanied by the use of renewable electricity with a very low CO_2 emission factor, good conduct in high risk procurement and sustainable supply chain systems, an application in the transport sector could be conceivable, at least in certain subsectors. In air and maritime transport, the direct use of renewable electricity is not possible (or only to a very limited extent), so that niches for e-fuels could form there. But even in these subsectors, electro-microbial fuels would have to outperform purely electrochemically produced e-fuels. Since the views on electro-microbial fuels, as expressed in a public perception survey conducted by [Schmidt & Youssef 2020], were generally rather positive, especially if used in aviation, concepts such as eForFuel could indeed gain the support of the EU population. However, such concepts will only be able to fly if major regulatory gaps in the context of RED II are closed in due time.

7.2. Recommendations

On the basis of the above conclusions, the following recommendations can be made to involved stakeholders:

To process developers and the 'Formate Bioeconomy' community

The present study, and in particular the identification of hot spots or optimisation potentials, shows that a number of research and development steps are still necessary on the way to a 'Formate Bioeconomy' from an environmental protection point of view. These include:

- The electroreactor is responsible for major parts of the overall sustainability impact of e-fuels due to the low conversion efficiency and especially the high demand for renewable electricity. Important steps for improving the sustainability of the eForFuel concept would be technical breakthroughs in the electroreactor. The goal would be to significantly increase the conversion efficiencies of electricity and CO_2-C to formic acid in order to reduce the enormously high specific electricity demand and to minimise the recycling of gases, electrolyte and water. Besides a large impact on the environment, the electricity used represents the greatest factor in terms of social risks as well as the economic profitability of the e-fuels produced.
- Technical breakthroughs in the bioreactor: after the focus of the eForFuel project was mainly on strain development of microorganisms, the focus of future research activities should also be increasingly directed towards technical challenges around reactor design. The concept of relying on gaseous target products that escape independently from the fermentation broth, which seems obvious at first glance, is currently hampered by the fact that the target product is present in a gas mixture in very low concentration and must be separated in a very energy-intensive process. A process concept is currently only available for the separation of isobutene, but not for the separation of propane. R&D efforts are still needed here, including the testing of membrane processes.
- Selection of target products: The goal of the eForFuel project was to develop renewable hydrocarbon fuels, especially for road transport. However, it became apparent that these can only offer climate change benefits at all under very specific conditions, both in comparison to conventional (fossil) fuels and in comparison to battery electric vehicles. The same presumably applies to other hydrocarbons (including chemicals), which can be extracted from crude oil and natural gas with relatively little expenditure or produced electrochemically in the future [Rosental et al. 2020]. However, the assessment could be different if it were possible to obtain more highly oxidised molecules from formic acid by means of biotechnological processes, which require less formate as a costly and less efficient reducing agent, and/or to obtain higher-quality, more complex molecules whose conventional equivalents are associated with large environmental footprints. Thus, applications in the direction of classic bio-based products, but bypassing primary agricultural production, seem promising. These could also be proteins used as food and animal feed, for example [Leger et al. 2021; Mishra et al. 2020].

To the CCU community in general

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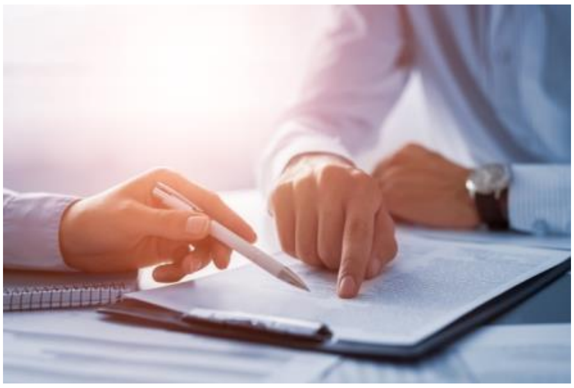
- The present study shows that synthetic fuels / e-fuels / PtX fuels are neither environmentally friendly nor socially sustainable per se, i.e. just because renewable resources are used for their production. Even if renewable resources are often associated with a low environmental burden, they are not entirely 'burden-free' or 'CO_2-neutral'. A sparing use of renewable electricity is also imperative from an economic point of view, especially when targeting fuels which are considered low added-value, high volume products with low profit margin.
- Renewable electricity will remain a scarce resource for the foreseeable future, which inevitably raises the question of how to use it most efficiently. Future R&D efforts should therefore aim to minimise the specific electricity demand and target those products whose conventional counterparts are associated with large environmental and social footprints or which are used in sectors where there are no or few other renewable alternatives.
- Considering the large amounts of electricity that will be needed for not only for synthetic fuels but also for the defossilisation of other sectors, it seems plausible that either electricity or electricity-based intermediates such as H_2 have to be imported into the EU. The CCU community should start, join or support primarily political initiatives for an environmentally and socially sustainable future procurement of these new energy carriers.
- Once e-fuel concepts are being upscaled to an industrial level of production, a socially sustainable procurement strategy has to be established also for inputs beyond electricity such as K_2SO_4 and fermentation media in this case. Certifications of suppliers according to standards such as those of the Global Reporting Initiative (GRI) are an important element in this strategy. This is also to the benefit of industrial actors themselves because they are increasingly held accountable for violations of social standards in their supply chains.

To political decision-makers

- In addition to the ongoing energy transition in the electricity sector, which is already causing growing resistance among the population, further enormous amounts of renewable electricity will be needed for the defossilisation of the heating and industry sectors in particular. Therefore, for each application, the climate-neutral renewable solution with the highest possible energy efficiency should be promoted in order to minimise associated environmental burdens and social risks. Furthermore, it is important to keep an eye on the entirety of all sectors and transitions as well as on the overall environmental impacts by means of forward-looking studies / long-term scenarios.
- Even with high efficiency, the electrification of the transport sector and other sectors such as heat and chemicals will foreseeably require enormous additional amounts of renewable electricity. Since this is central to the development towards a simultaneously climate-neutral, competitive and social Europe, an overall strategy and implementation plan for future-proof renewable electricity provision must be developed with very high priority. The project under consideration here is just one of many examples whose future depends, among other things, on the success of the energy transition.

- In this regard and from a social point of view, a better balance must be found between the interests of, for example, direct neighbours of wind turbines and the population as a whole (as users of electricity and electricity-based products), so that resistance from parts of the population diminishes and renewable energies can be further expanded. This could be achieved, e.g. through participation of citizens in profits via cooperatives.
- For the overall strategy for a reliable, competitive and socially beneficial provision of renewable electricity for Europe, it may be reasonable to include countries from the Middle East and North Africa (MENA region). This could be done by importing energy-intensive intermediate products such as hydrogen, which would only be indirectly relevant for the concept considered here by reducing the pressure on the electricity market, because a long-distance transport of the intermediate formate would hardly be technically feasible in this case.
- From a social point of view, a possible future import of electricity from e.g. North Africa could offer great opportunities and lead to a win-win situation. However, adequately addressing existing substantial risks requires reliable cooperation at equal level and is difficult to achieve by individual companies. Among the risks, the focus should be on the resolution of armed conflicts, the legal system of the respective countries, and corruption, which have also emerged as hot spots in this analysis. Here, European policy is required to go new ways beyond previous development cooperation. It will be crucial to respect the needs and choices of local stakeholders and communities because otherwise cooperation with best intentions is likely to be perceived as neo-colonialism. In this context, it is also important to learn from failed initiatives such as Desertec.
- The most significant barriers to implementation of the eForFuel concept result from the legal uncertainty, which is due to an absence of legislation in the context of the Renewable Energy Directive (RED II). A number of open issues related to Articles 25, 27 and 28 of the RED II cause uncertainty of entrepreneurs what might affect the short- and medium-term market deployment of eForFuel products. These issues should be resolved with high priority and pending delegated acts should be adopted soon.
- For a sustainable future perspective of e-fuels, it is however most important to create a support scheme that does not contain regulatory loopholes rather than having a regulation in place quickly. In particular, it must be avoided that the interplay between the EU ETS Directive (Directive 2003/87/EC) and the RED II leads to neither counting fossil CO_2 emissions in delivering sectors such as steel and concrete plants nor in the receiving fuel sector. This could severely damage the public acceptance of Carbon Capture and Utilisation technologies.



8. Abbreviations

ASU	Air separation unit
BEV	Battery electric vehicle
BF (gas)	Blast furnace (gas)
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CFC	Chlorofluorocarbon
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Direct air capture
DoA	Description of Action
EBITDA	Earnings before interest, taxes, depreciation, and amortization
EU	European Union
EC	European Commission
FT	Fischer Tropsch
GA	Grant Agreement
GHG	Greenhouse gas
GMO	Genetically modified organism
GRI	Global Reporting Initiative
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water
HCOOH	Formic acid
ICEV	Internal combustion engine vehicle
IE	Inhabitant equivalents
ILCD	International Reference Life Cycle Data System
ILCSA	Integrated Life Cycle Sustainability Assessment
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LPG	Liquefied petroleum gas
LU	Land use
LUC	Land use change
MEA	Monoethanolamine
MENA	Middle East and North Africa
MJ	Megajoule
MW	Megawatt
N_2	Nitrogen
NREU	Non-renewable energy use
O_2	Oxygen
PtH	Power-to-Heat: conversion of electricity to heat
PtX	Power-to-X: conversion of electricity to liquid or gaseous secondary energy carriers
PV	Photovoltaics
RCF	Recycled carbon fuel, as defined in the RED II, Article 2(35)
RE	Renewable electricity
RED	Renewable Energy Directive [European Parliament & Council of the European Union 2009]
RED II	Renewable Energy Directive [European Parliament & Council of the European Union 2018]
RFNBO	Renewable fuel of non-biological origin, as defined in the RED II, Article 2(36)
SHDB	Social hotspot database
SWOT	Strengths, weaknesses, opportunities, threats
TEA	Techno-economic assessment
WP	Work package

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10. Annex

The following figures (Figure 17 - Figure 19), prepared by C3 Biotechnologies Ltd, display the mass and energy flows diagrams for the three main routes under typical and optimistic boundary conditions.

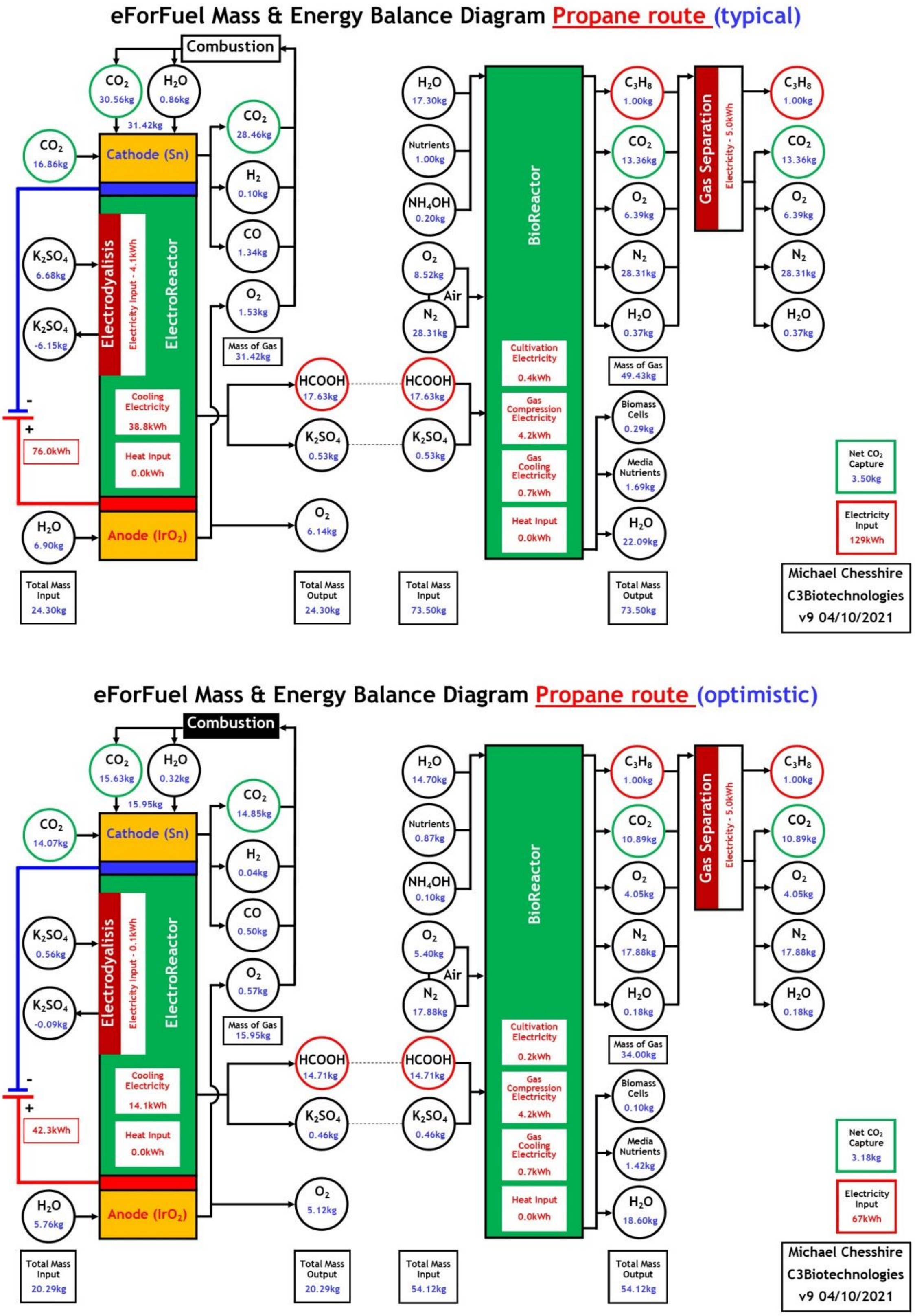


Figure 17: Mass and energy balance diagram for the propane route under typical (upper panel) optimistic technology development (lower panel)

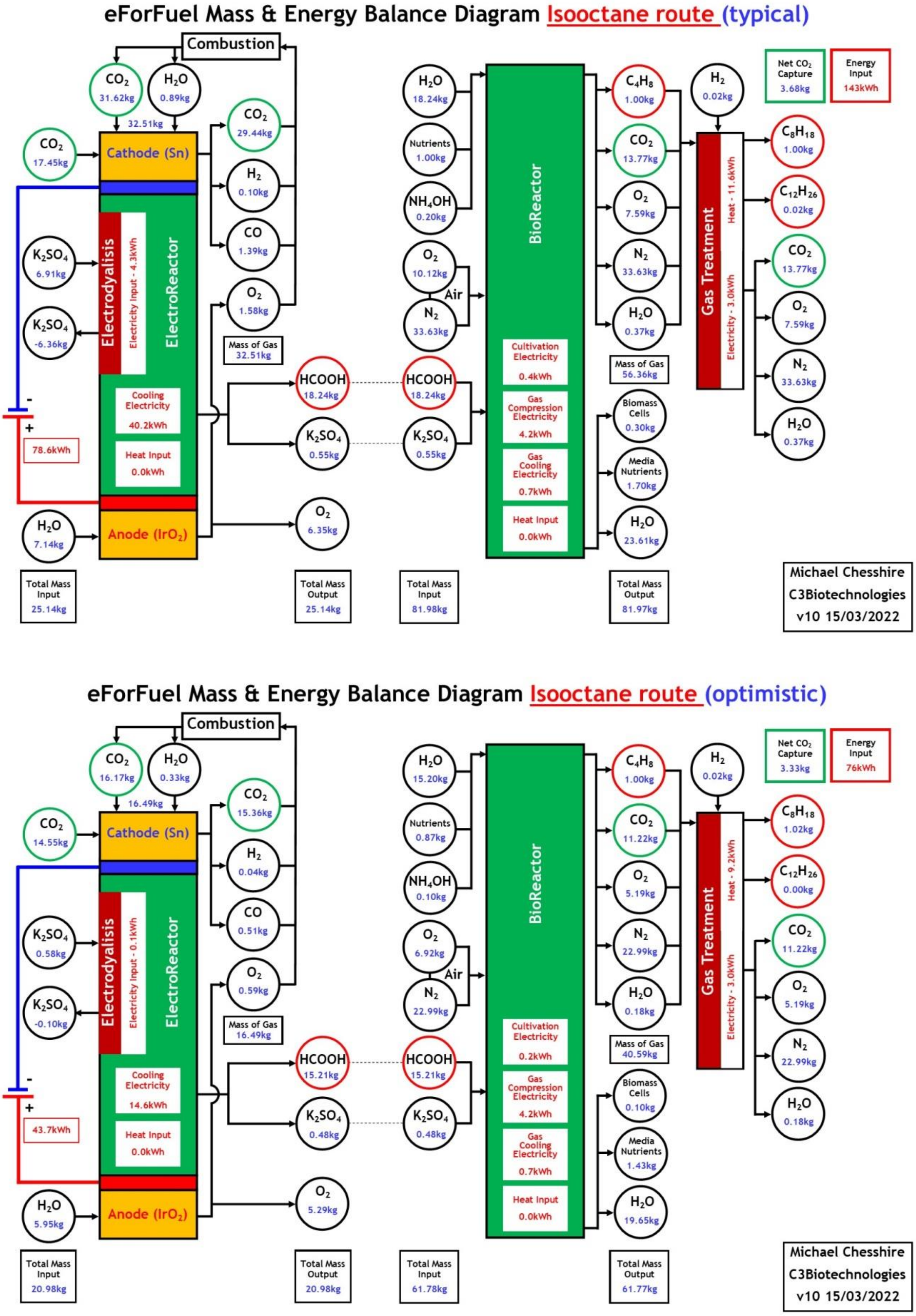
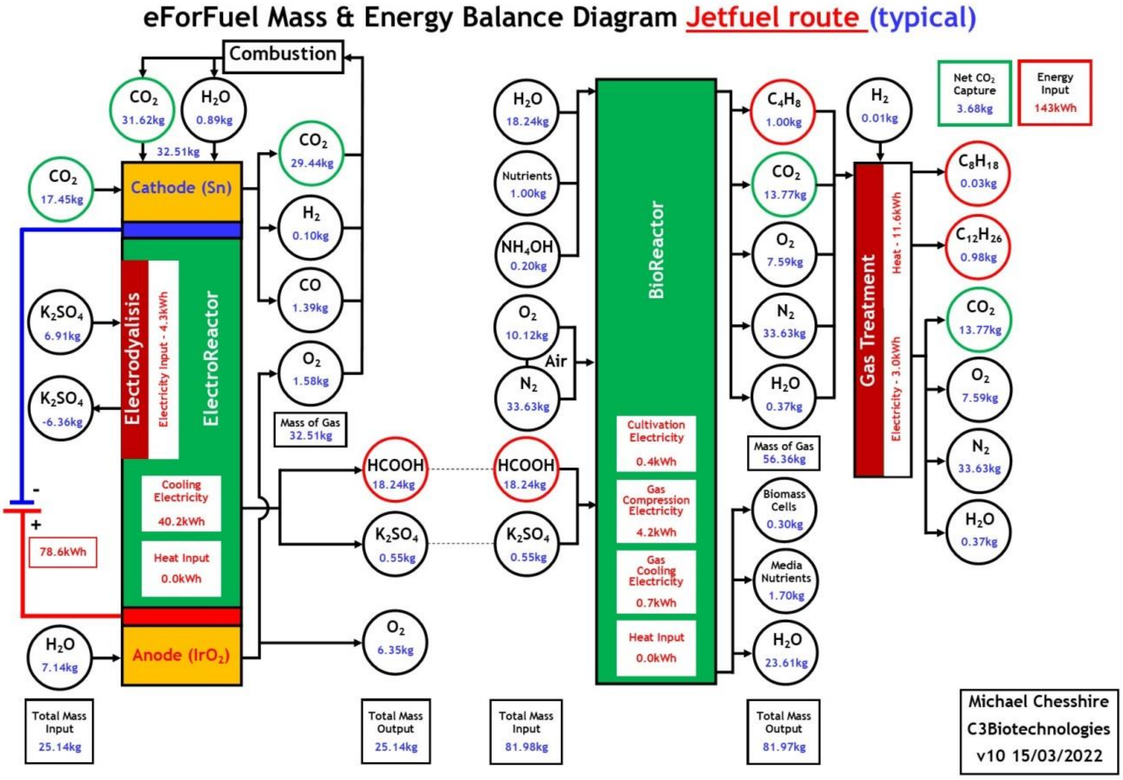


Figure 18: Mass and energy balance diagram for the isooctane route under typical (upper panel) optimistic technology development (lower panel)



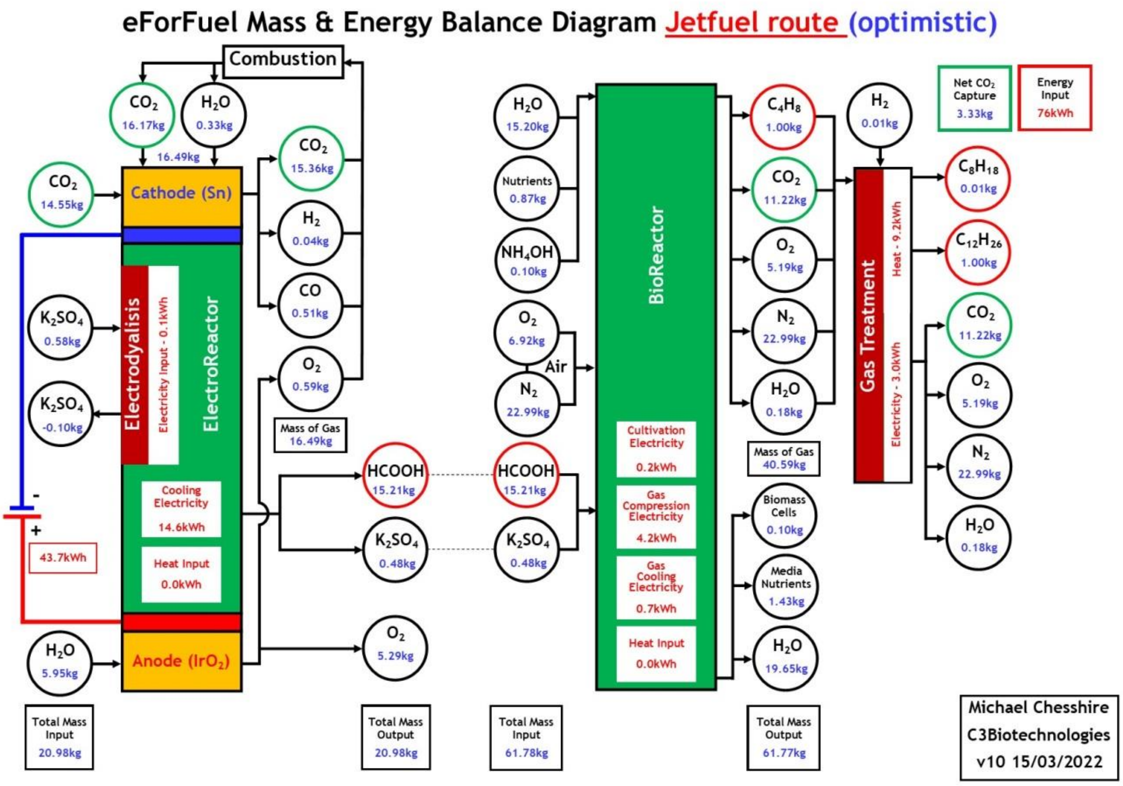


Figure 19: Mass and energy balance diagram for the jetfuel route under typical (upper panel) optimistic technology development (lower panel)