PROJECT ACRONYM

eForFuel

PROJECT TITLE

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

Deliverable 5.2

Report on life cycle assessment

CALL ID			H2020-LCE-2017-RES-RIA
GA No.			763911
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NATURE	Report (R)	DISSEMINATION LEVEL	PU
DUE DATE	31/08/2021	ACTUAL DELIVERY DATE	30/09/2021
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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 763911.

Table of Revisions

REVISION NO.	DATE	WORK PERFORMED	CONTRIBUTOR(S)
1	03/09/2021	First draft	Nils Rettenmaier, Bernd Franke, Sven Gärtner, Heiko Keller, Guido Reinhardt
2	30/09/2021	Final version	Nils Rettenmaier, Bernd Franke, Sven Gärtner, Heiko Keller, Guido Reinhardt

Cooperation between participants

This deliverable D5.2 "Report on life cycle assessment" has been prepared by IFEU and presents the results of IFEU's work under Task 5.2. The screening life cycle assessments were performed on the basis of mass and energy flow data which were provided by MPG, b.fab, USTUTT, SINTEF, GBE.

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

Acknowledgements

The authors would like to thank all eForFuel project partners sincerely for the provision of information and data, which forms the basis of this life cycle assessment, notably the mass and energy flow data provided by Arren Bar Even (MPG), Frank Kensy (b.fab), Elias Klemm and Marvin Oßkopp (USTUTT), Paul Inge Dahl and Thulile Khoza (SINTEF), Antonio Sepúlveda-Escribano and Mercedes Pastor-Blas (UA) as well as Macha Anissimova, Denis Thibaut, Frédéric Ollivier, Romain Chayot and Marcus Zang (GBE). Furthermore, we are grateful to Michael Chesshire (C3BT) who kept a vigilant eye on the mass and energy flow data. Last but not least, we would like to thank our IFEU colleagues Sonja Haertlé and Christina Zinke for their support as well as Kirsten Biemann, Thomas Fröhlich, Axel Liebich, Daniel Münter and Marian Rosenthal for providing LCI data.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the grant agreement No. 763911.

Horizon 2020
European Union Funding
for Research & Innovation

Life Cycle Assessment of Electro-Microbially Produced Transport Fuels

This report was produced as Deliverable 5.2 within Work Package 5 “Integrated sustainability assessment” of the EU-funded project eForFuel (“Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons”)

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Suggested citation:

Rettenmaier, N., Franke, B., Gärtner, S., Keller, H., Reinhardt, G. (2021): Report on Life Cycle Assessment: “Life Cycle Assessment of Electro-Microbially Produced Transport Fuels”. In: eForFuel project reports, supported by the EU’s Horizon 2020 programme under GA No. 763911, ifeu – Institute for Energy and Environmental Research Heidelberg, Germany, available at: https://www.ifeu.de/en/project/eforfuel

Heidelberg, September 2021

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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 life cycle sustainability assessment (ILCSA). One essential element of this is the life cycle assessment (LCA) which is presented here.

The aim of this LCA study is to assess the potential environmental impacts associated with the implementation of the eForFuel concept in the future. To cover the full breadth of the concept, three different electro-microbial fuels were investigated. The main objective of the LCA study is to determine whether or under which conditions the eForFuel concept is more environmentally sustainable than conventional (fossil) fuel provision. Another important goal of the LCA study is to identify optimisation potentials from an environmental point of view to determine focal areas for the further development of the eForFuel concept.

Selected results of the LCA study:

- The screening LCAs 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 conditions include that the energy used for electricity and heat is associated with low CO_2 emissions. The CO_2 emission factor of the renewable electricity used determines whether a favourable GHG balance can be achieved. For significant GHG emission savings compared to fossil fuels, an emission factor of <15 g CO_2eq / kWh electricity is necessary, which can currently only be realised with offshore wind power.

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- In addition to the low efficiencies of electroreactor and bioreactor, the accounting of the co-product oxygen is decisive to determine advantages or disadvantages with regard to climate change. If in the future a credit for the avoided environmental burdens of substituted, conventionally produced oxygen at the current level is no longer justified, GHG emission savings would be significantly reduced, so that the overall GHG balance could turn out to be unfavourable.

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- The aforementioned potential environmental benefits related to climate change and energy use are always associated with negative environmental impacts, e.g. in terms of phosphate rock use and water use. This applies equally to all three electro-microbial fuels that were investigated.
- In this way, the LCA provides valuable insights for the further development of the eForFuel concept, e.g. by identifying optimisation potentials along the value chain. The efficiencies of both the electro-reactor and the bioreactor, i.e. the concept's core components, were identified as focal areas.
- In the Renewable Energy Directive (RED II), the European Commission is required to adopt a delegated act establishing appropriate minimum thresholds for GHG 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 determine whether the electro-microbial fuels considered comply with the GHG emission saving criteria set forth in the RED II.
- The life cycle comparison between electro-microbial fuels and biofuels show that neither one nor the other has genuine advantages. Thus, from an environmental point of view, there is presently no clear winner. Life cycle comparisons with other renewable fuels and alternative powertrains indicate that electro-microbial fuels (eForFuel concept) have a significantly lower efficiency in electricity use, both compared to purely electrochemically produced hydrocarbon fuels (by means of water electrolysis and subsequent fuel synthesis) and compared to battery electric vehicles (BEV). This is associated with correspondingly lower GHG emission savings.

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- The quantities of electro-microbial fuels that can be produced in Europe in the future will be far from sufficient to satisfy today's fuel demand (especially that of road transport). This is because the two main resources - at least in Europe - are limited and subject to competition: (i) renewable electricity or suitable sites on land and at sea for its expansion and (ii) CO_2 from large point sources.

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Selected conclusions on the basis of these results are:

- Innovative e-fuels for transportation are not environmentally friendly *per se*, i.e. just because renewable resources are used for their production. Even though renewable resources often have a low environmental burden, they are not entirely 'burden-free' or 'CO_2-neutral'. The investigated electro-microbial fuels can only achieve GHG emission savings compared to conventional fuels provided that
  (i) the energy used is associated with low CO_2 emissions, i.e. <15 g CO_2eq / kWh electricity
  (ii) a substantial credit can be achieved for the substituted conventionally produced oxygen.
  All optimisation potentials along the entire value chain must be fully tapped, especially to reduce the enormously high electricity demand.

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- Prospects for electro-microbial fuels in the transport sector are only conceivable from an environmental protection point of view if the eForFuel concept is significantly improved. This is because the investigated electro-microbial fuels
  (i) do not achieve any genuine advantages over biofuels
  (ii) show clear disadvantages if compared to purely electrochemically produced hydrocarbon fuels (by means of water electrolysis and subsequent fuel synthesis) and and also to battery electric vehicles (BEV).

- The future use of electro-microbial fuels in the transport sector is - if at all - only conceivable for air and maritime transport and for specific subsectors of road transport, where the direct use of renewable electricity is not possible or only possible to a very limited extent. The reason for this is that the quantities of electro-microbial fuels that can be produced in Europe can at best replace a small part of today's fuel demand due to the limited potential of (i) renewable electricity (as well as areas for its expansion) and (ii) of CO_2 from large point sources. Even in these areas, purely electrochemically produced e-fuels would be superior to fuels based on the eForFuel concept – at least from today's perspective.

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Main recommendation from an environmental perspective: The *Formate Bioeconomy* community should focus its R&D efforts on technical breakthroughs in both electroreactor and bioreactor and target products whose conventional counterparts are associated with large environmental footprints. Further recommendations, differentiated according to different stakeholders, are made in section 6.3.

Key deliverable achievements:

1. Assessment of potential environmental impacts 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 hot spots (unit processes that dominate the results significantly) and optimisation potentials from an environmental protection point
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.

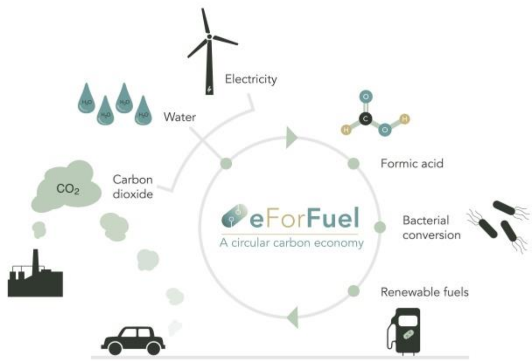

Figure 1: The eForFuel concept

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 included an integrated life cycle sustainability assessment (ILCSA) to assess potential sustainability impacts associated with the implementation of the eForFuel concept in the future. The 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 life cycle assessment' (Deliverable D 5.2) covers the assessment of environmental impacts along this life cycle. Together with the 'Report on techno-economic assessment' (Deliverable D 5.3) and the 'Report on social and policy assessment' (Deliverable D 5.4), it forms the foundation for the subsequent integrated sustainability assessment. 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 LCA study is to determine whether or under which conditions the eForFuel concept is more environmentally sustainable than conventional (fossil) fuel provision. Another important goal of the LCA study is to identify optimisation potentials from an environmental point of view to determine focal areas for the further development of 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. The report closes with conclusions and recommendations in chapter 6.

3. Methods

The integrated sustainability assessment in eForFuel is conducted according to [Keller et al. 2015]. 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 3.1. Specific definitions and settings that are only relevant for the environmental assessment are described in chapter 3.2.

3.1. 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 environmental assessment.

3.1.1. 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.

3.1.2. 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 2). 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.

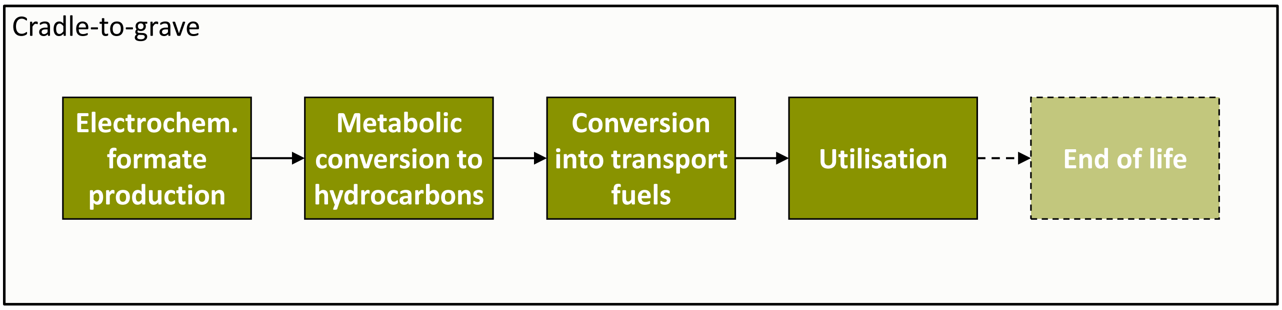

Figure 2: System boundary (cradle-to-grave) applied within the eForFuel project.

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 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 ('n^{th} 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: USTUTT, SINTEF, UA
- Bioreactor: MPG, BFAB
- Product separation: GBE

3.2. Specific definitions and settings for LCA

The screening life cycle assessment (LCA) is based on international standards such as [ISO 2006a; b] and the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012]. In the following, specific settings and methodological choices are detailed.

3.2.1. Introduction to LCA methodology

Life cycle assessment (LCA) is structured, comprehensive and internationally standardised through ISO standards 14040:2006 and 14044:2006 [ISO 2006a; b]. The LCA within the eForFuel project is carried out largely following these ISO standards on product life cycle assessment. According to the ISO standards, a LCA consists of four iterative phases (Figure 3):

- Goal and scope definition (see section 3.2.1),
- Inventory analysis (see section 3.2.2),
- Impact assessment (see section 3.2.3), and
- Interpretation (see chapter 5).

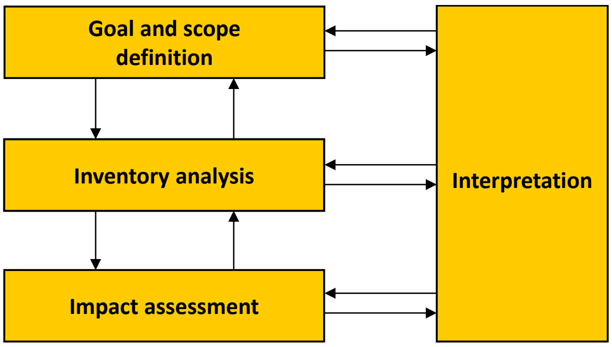

Figure 3: Phases of an LCA [ISO 2006a; b]

The ISO standards 14040 and 14044 provide the indispensable framework for life cycle assessment. This framework, however, leaves the individual LCA analysts with a range of choices, which can affect the legitimacy of the results of a LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance.

The International Reference Life Cycle Data System (ILCD) Handbook [JRC-IES 2012] has therefore been developed to provide guidance and specifications that go beyond the ISO standards 14040 and 14044, aiming at consistent and quality-assured life cycle assessment data and studies. The screening LCA study carried out within the eForFuel project takes into account the major requirements of the ILCD Handbook following these considerations of flexibility and strictness. The analyses in this study are so-called screening LCAs which follow the above mentioned ISO standards except for a) the level of detail of documentation, b) the quantity of sensitivity analyses and c) the mandatory critical review. Still, the results of these screening LCAs are suitable to answer the goal questions reliably due to the close conformity with the ISO standards.
Recently, specific guidelines for LCA studies on carbon capture and utilisation (CCU) have been published [Ramirez Ramirez et al. 2020; Zimmermann et al. 2020]. Those were taken into account as well.

3.2.2. Settings for Life Cycle Inventory (LCI)

Settings for Life Cycle Inventory include the following aspects:

- I Data sources
- II Attributional vs. consequential modelling
- III Co-products handling
- IV Land use and land use changes associated with biogenic reference products
- V Modelling carbon flows to and from the atmosphere

I Data sources

In addition to the primary data outlined in section 3.1.2, further (secondary) data such as on background processes were taken from IFEU's internal database [IFEU 2021] (e.g. the CO_2 emission factors for electricity in Table 1), from the ecoinvent database [Ecoinvent 2020] and from literature data where necessary.

- Iridium: [Nuss & Eckelman 2014]
- CO_2 capture, PEM electrolysis: [Liebich et al. 2021]
- Battery electric vehicle (BEV), internal combustion engine vehicle (ICEV) [Kämper et al. 2020]

Table 1: CO_2 emission factors for different exemplaryelectricity sources used in this study

Electricity	g CO_2 eq / kWh	Source
Wind power (offshore)	19.8	[IFEU 2021], modified from [Ecoinvent 2020]
Wind power (onshore)	35.5	[IFEU 2021], modified from [Ecoinvent 2020]
Photovoltaics (Lisbon)	52.2	[IFEU 2021], modified from [Ecoinvent 2020]
Photovoltaics (Munich)	81.4	[IFEU 2021], modified from [Ecoinvent 2020]
Power mix EU 2030	241.9	[IFEU 2021], based on [European Commission 2016]

II Attributional vs. consequential modelling

The sustainability assessment can follow a consequential or attributional approach, which has implications for the methodological approach for co-products, indirect effects, etc., especially in LCA. Consequential modelling is more extensive and 'aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy' according to ILCD Handbook [JRC-IES 2010]. Consequential modelling is recommended for decision-contexts where influential impacts are expected on a meso/macro-level [JRC-IES 2010]. This is the case for the eForFuel systems. Hence, a consequential modelling approach is applied in this assessment.

There is only one exception to this: The accounting principles of the Renewable Energy Directive (RED II) stipulate that an attributional modelling approach is chosen [European Parliament & Council of the European Union 2018].

III Co-products handling

As explained in section 3.1.2, the system boundary includes all products and co-products. For each usable co-product produced, the environmental burdens of the main product need to be reduced. The general alternatives concerning this procedure of co-product handling are exemplarily illustrated in Figure 4. System expansion is applied, which according to ISO standards for LCA [ISO 2006a; b] is preferred over allocation: the impacts of a multi-output system are balanced with the avoided impacts of the reference products that are replaced by the products of the multi-output system.

Deviating from this general setting, the accounting principles of the Renewable Energy Directive (RED II) stipulate that multi-output processes are resolved by allocating the burdens among co-products according to their energy content [European Parliament & Council of the European Union 2018].

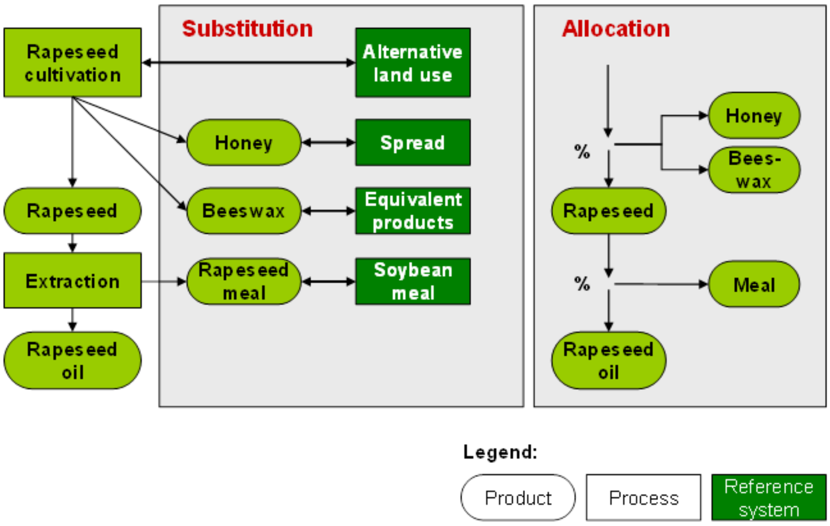

Figure 4: Exemplary illustration of methodological approaches for co-product accounting.

IV Land use and land use changes associated with biogenic reference products

According to the system description in chapter 4, the electro-microbial fuels are not only compared to conventional (fossil) fuels but also to biofuels. For the production of crop-based biofuels, land is required for the cultivation of sugar, starch or lignocellulosic crops. Apart from land occupation (land use, LU), also land transformation (land use changes, LUC) is induced. Land use change (LUC) and land use (LU), in particular of organic soils, lead to emissions beyond those caused by cultivation of crops as such. These have to be taken into account for any LCA of agricultural systems.

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Unless otherwise indicated, a recently developed methodological approach abbreviated as 'attributional land use and land use change (aLULUC)' is applied for the inventory analysis. An elaborate explanation and discussion is reported in [Fehrenbach et al. 2020]. The main idea is to evenly allocate the burdens associated with both the use of agricultural land[1] and the land use changes that have taken place in one country to all agricultural land use of that country. Thus, for each country and class of agricultural land (e.g. annual cropland, grassland) one emission factor per hectare per year is obtained. The aLULUC approach was developed for standard agricultural land and is mainly applied for the biogenic reference product (e.g. bioethanol) in the eForFuel project.

Deviating from this general setting, the accounting principles of the Renewable Energy Directive (RED II) stipulate the accounting of annualised emissions from carbon stock changes caused by direct land-use change (dLUC) only [European Parliament & Council of the European Union 2018]. Continuous emissions from land use (LU) on drained organic soils / peatland are not accounted according to the calculation rules of the RED II.

[1] Mainly because of continuous emissions due to the agricultural use of organic soils.

V Modelling carbon flows to and from the atmosphere

According to [Ramirez Ramirez et al. 2020], the carbon flows and pools affected by CCU system shall be described In eForFuel, three sources of carbon dioxide are investigated:

- Fossil CO_2 originating from a steel plant
- Biogenic CO_2 originating from fermentation or anaerobic digestion (+methanation)
- Atmospheric CO_2 captured by Direct Air Capture (DAC) units

Using the latter two does not affect the atmospheric carbon pool (and hence global warming) since the produced fuels are combusted and the captured CO_2 (either by biomass or technical system) is returned to the atmosphere. Of course, the CO_2 capture and especially CO_2 activation requires large amounts of energy which – even if 100% renewable – is not entirely 'burden-free' or 'CO_2 neutral'. Emitting CO_2 from fossil origin, however, increases the atmospheric carbon pool (and hence global warming). This requires that the environmental burden of the CO_2 has to be accounted for, either by the emitting system (here: steel plant) or by thereceiving system (here: eForFuel) or by both systems.

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In this study, CO_2 of non-renewable origin is set to be a waste (it is inevitably and unintentionally produced as a result of a production process in a steel plant) and the environmental burdens associated with CO_2 remain with the main and co-products of the emitting process, i.e. with the steel. Moreover, diverting CO_2 from the steel plant does not change the steel plant's possibility to generate energy from its waste gases since CO_2 has no heating value. Thus there is no change in the reference system and thus no penalty associated with the CO_2. Only the expenditures for CO_2 capture are attributed to the eForFuel system.

3.2.3. Settings for Life Cycle Impact Assessment (LCIA)

According to ISO standard 14040 [ISO 2006a], life cycle impact assessment (LCIA) includes the mandatory steps of classification and characterisation as well as the optional steps of normalisation and weighting. Classification and characterisation depend on the chosen impact categories and LCIA methods. Regarding the optional elements, only the normalisation step is applied within the eForFuel project. The corresponding specifications of these LCIA elements are described in the following sections including

- I Impact categories and LCIA methods
- II Normalisation
- III Weighting.

I Impact categories and LCIA methods

All main environmental issues related to the eForFuel value chains should be covered within the impact categories of the screening life cycle assessment in a comprehensive way. Furthermore, the impact categories must be consistent with the goal of the study and the intended applications of the results. This project assesses the midpoint indicators listed in Table 2.. The LCIA methods follow the recommendations in [Detzel et al. 2016].

Potential environmental impacts can be analysed at midpoint or at endpoint level. For the environmental assessment within the eForFuel project, the midpoint level is considered as more suitable than the endpoint level because the impacts are analysed in a more differentiated way and the results are more accurate. The specific impact categories at midpoint level are chosen according to the approach by [Detzel et al. 2016].

Table 2: Overview on included midpoint impact categories.

Midpoint impact category	LCIA method
Non-renewable energy use	[Borken et al. 1999; VDI (Association of German Engineers) 2012]
Climate change	[IPCC 2013]
Acidification	[CML 2016]
Eutrophication, terrestrial	[CML 2016]
Ozone depletion	[Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010]
Particulate matter	[de Leeuw 2002]
Phosphate rock use	[Reinhardt et al. 2019]
Land use	[Fehrenbach et al. 2019]
Water use	[Boulay et al. 2018]

This set of methods also includes three long-neglected impact categories covering environmental issues: phosphate rock footprint, land use footprint and water footprint:

- The phosphate rock demand is dominated by phosphorus requirements of agricultural processes or fermentation processes and but other life cycle stages may also play an important role. The associated impacts on phosphorus resources are covered by the impact category ‘phosphate rock footprint’ [Reinhardt et al. 2019].
- Impacts on natural land use are addressed by the hemeroby approach according to [Fehrenbach et al. 2019]. This approach includes both the degree of human influence on a natural area and the distance of that area to the undisturbed state.
- The water scarcity footprint is calculated based a water use midpoint indicator representing the relative Available WAter Remaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met [Boulay et al. 2018].

In this screening LCA, however, some impact categories are excluded for various reasons: Impact categories that are irrelevant for the eForFuel value chains are excluded from this study. This is the case for ionising radiation, for example. The reason behind this is that the selected impact categories should only cover the relevant environmental aspects of the eForFuel value chains to avoid an information overload.

Furthermore, impact categories are excluded (i) that are still under methodological development or (ii) that cannot ensure sufficient LCI data quality for the reference year 2030 (i.e. impact categories on toxicity). Specific issues on human health are nevertheless covered by the categories particulate matter formation and photochemical ozone formation.

II Normalisation

Normalisation in LCA is an optional step to better understand the relative magnitude of the results for the different environmental impact categories. To this end, the category indicator results are set into relation with reference information. Normalisation transforms an indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected country.

Within the eForFuel project, the value chains are characterised for Europe. Therefore, the resource demand and emissions per capita in the European region are chosen as reference for normalisation. Last available data from [Sala et al. 2015] are taken which refer to the year 2010 and the EU 28 countries (see Table 3).

Table 3: Overview on normalisation factors per person and year of the EU28 states in the reference year 2010 [Sala et al. 2015]

Midpoint impact category	Inhabitant equivalent values per person and year (EU28)	
Non-renewable energy use	34	GJ cumul. primary energy
Climate change	9.2	t CO_2 equivalents
Acidification	35	kg SO_2 equivalents
Eutrophication, terrestrial	5	kg PO_4 equivalents
Ozone depletion	0.06	kg CFC-11 equivalents
Particulate matter	28	kg $PM_{2.5}$ equivalents
Phosphate rock use	23	kg phosphate rock std.
Land use	0.24	m^2·yr artificial land equivalents
Water use	9364.4	m^3 water equivalents

III Weighting

Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis. Weighting is not applied in this study.

3.2.4. Greenhouse gas balances according to European legal requirements

In the light of a controversial discussion on the net benefit of biofuels and bioenergy and the share of renewable energy in the transport sector, the European Renewable Energy Directive (2009/28/EC, RED) on the promotion of the use of energy from renewable sources [European Parliament & Council of the European Union 2009] set out a mandatory share of 10% by and a number of sustainability criteria. These criteria had to be met by biofuels and bioliquids to be able to be counted towards the 10% target.

The RED has been substantially amended several times and recast in 2018 (RED II) [European Parliament & Council of the European Union 2018].The mandatory share of renewable energy in road and rail transport was increased to 14% by 2030. Moreover, 3.5% sub-target for advanced biofuels was included. Besides biofuels, two new categories of renewable fuels were introduced: renewable fuels of non-biological origin (RFNBOs) and recycled carbon fuels (RCFs). The sustainability criteria defined in the RED II are partly the same as in the original RED and partly new or reformulated. In particular, the RED II introduces sustainability criteria for forestry feedstocks as well as GHG criteria for solid and gaseous biomass fuels.

Within the eForFuel project, the climate change-related criteria of the RED II are most important: the greenhouse gas (GHG) emission savings from the use of biomass fuels. In the transport sector, the emission saving shall be at least 60% (after October 2015), increasing to 65% after January 2021 – including emissions from direct land use changes (dLUC) – compared to the defined emissions of the fossil fuel comparator. For RFNBOs as well as for electricity, heating and cooling, the emission saving shall be at least 70% after January 2021. The rules for calculating the GHG impact are defined in two annexes to the RED II: Annex V for biofuels and bioliquids and Annex VI for biomass fuels, respectively. These rules follow a more pragmatic approach and differ considerably from the ISO standards 14040 and 14044 (see section 3.2.2).

One of the original goals of this study (see section 3.1.1) was to check whether the investigated electro-microbial fuels comply with the minimum GHG emission savings set out in the RED II. However, the calculation methodology for RFNBOs and RCFs hasn't been adopted yet: the Commission is required to adopt the corresponding delegated act by 31 December 2021. A draft is expected to be published only in November 2021 [European Commission 2021].

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 alternative scenarios and reference 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 5 and Figure 6 for isooctane / isododecane (jet fuel) and propane, respectively. These are the three main routes investigated in eForFuel.

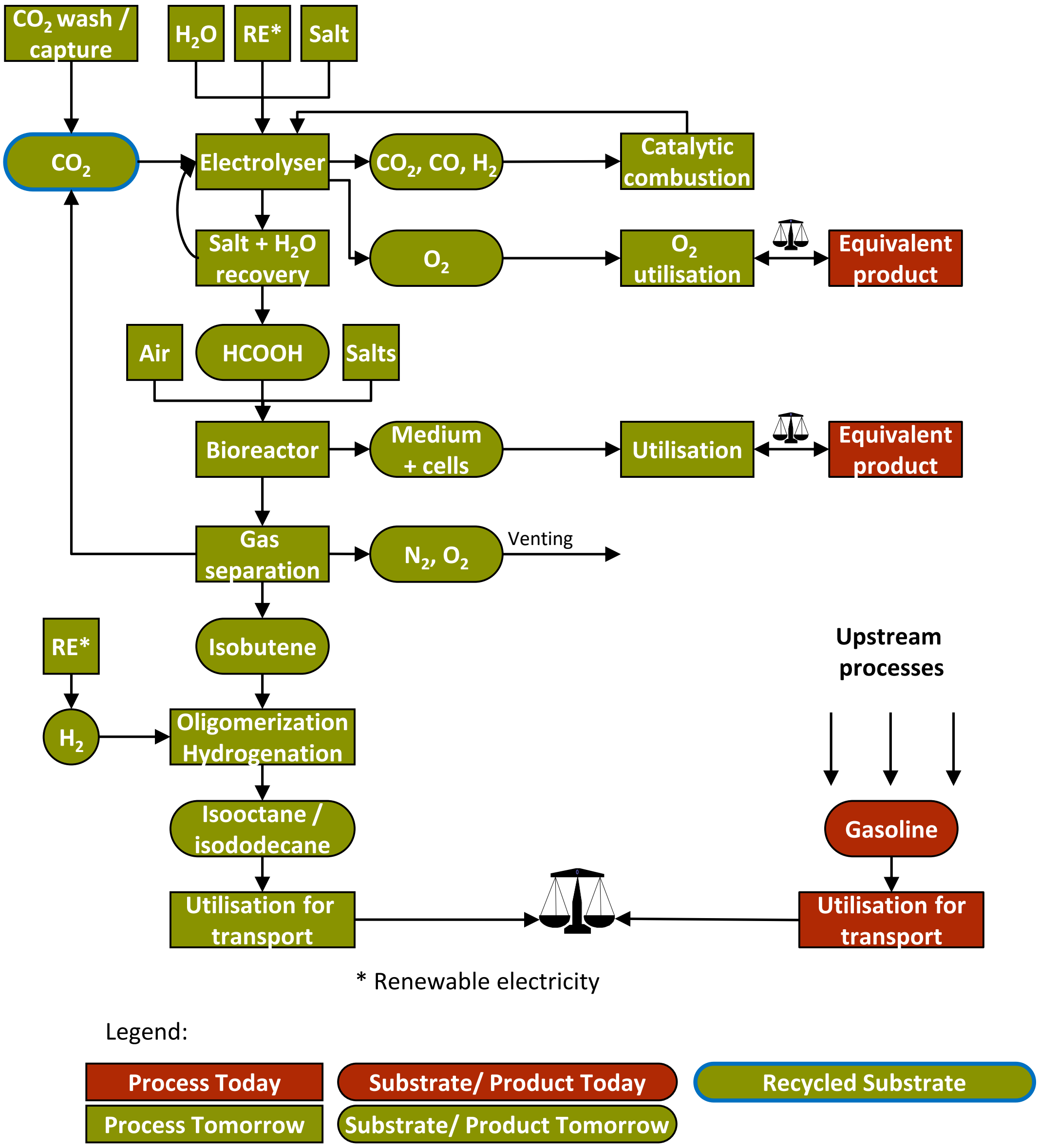

Figure 5: Simplified scheme of the isooctane route

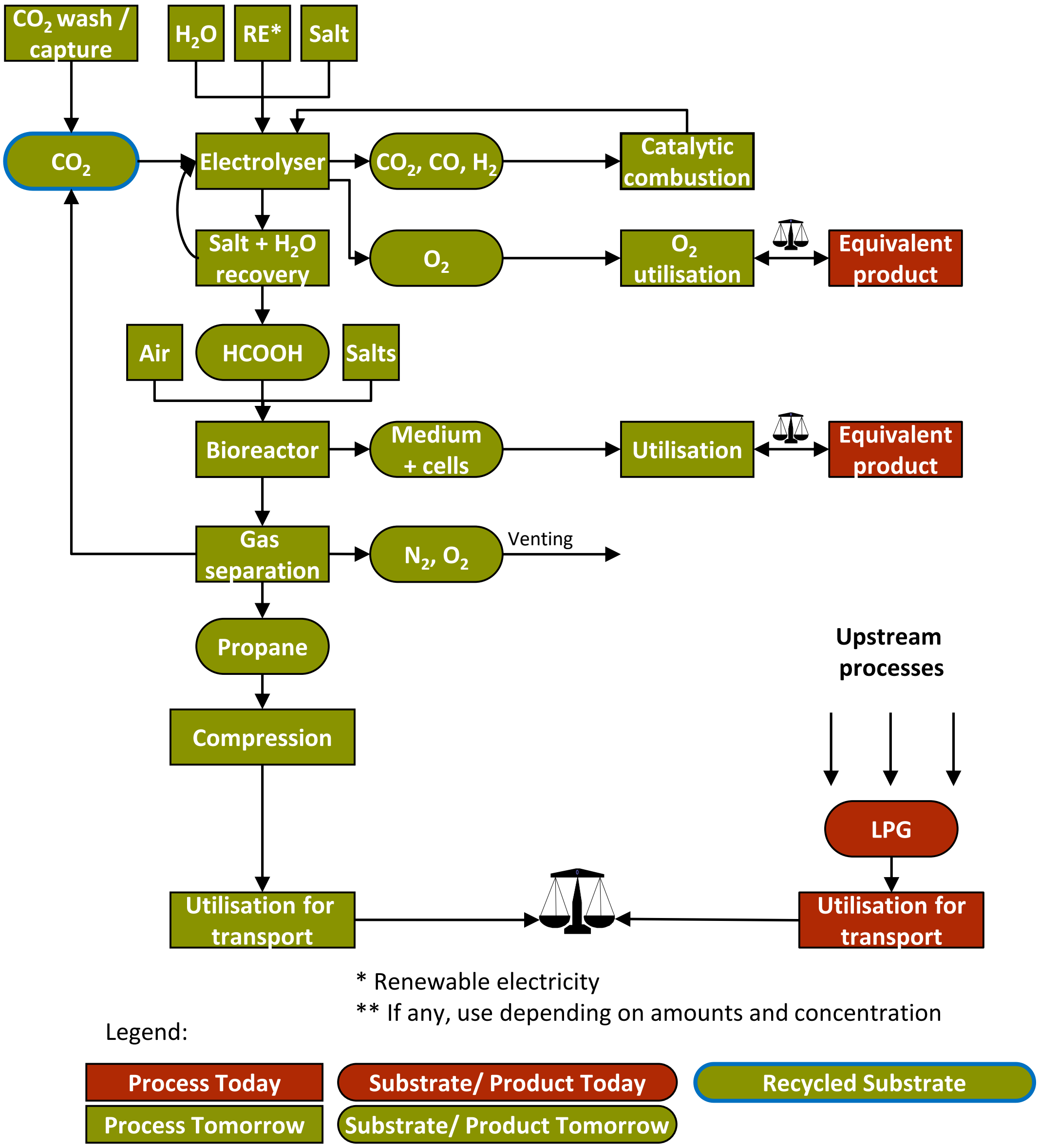

Figure 6: Simplified scheme of the propane route

4.2. Electrochemical production of formic acid (electroreactor)

The electrochemical production of formic acid (Figure 7) 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.

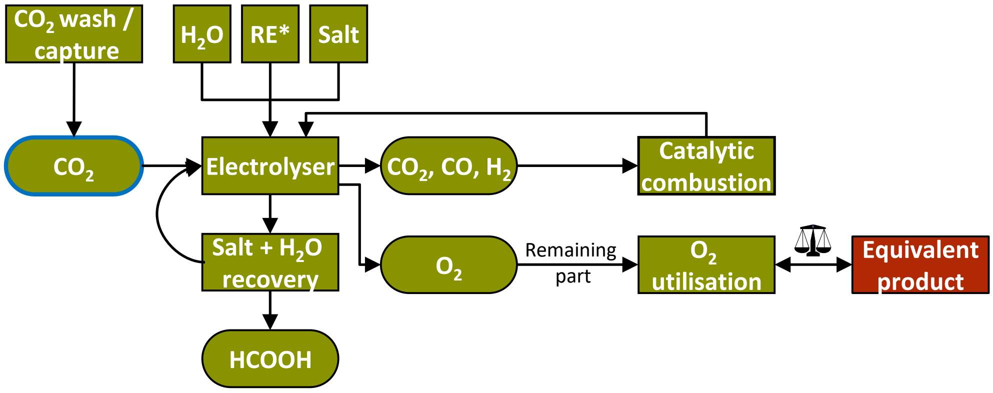

Figure 7: Electrochemical production of formic acid

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 8). Apart from formic acid, **inputs** of air, water (H_2O), salts (ammonium, phosphate and sulfate 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).

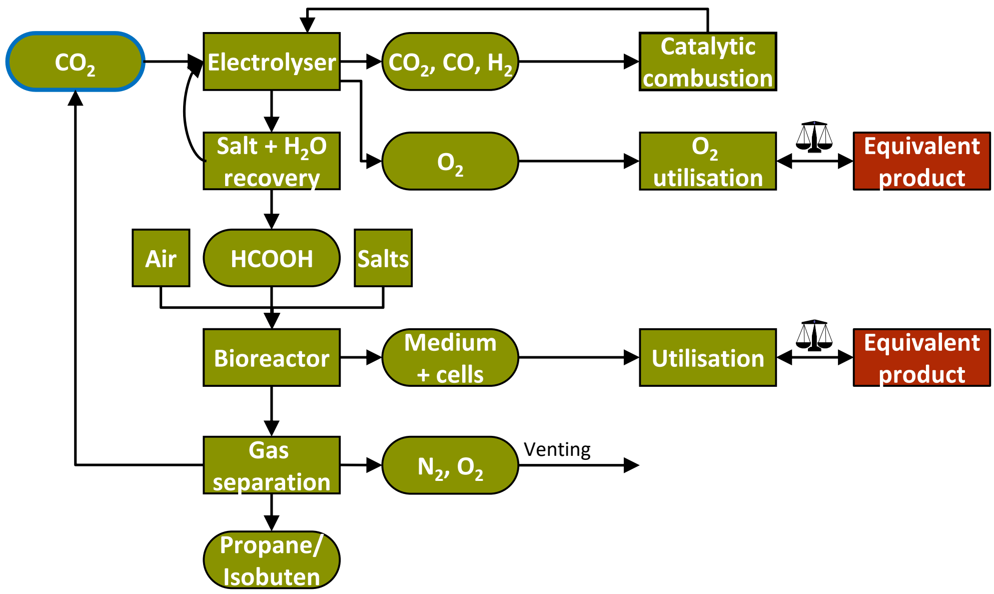

Figure 8: Metabolic conversion of formic acid into hydrocarbons

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 9). 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.

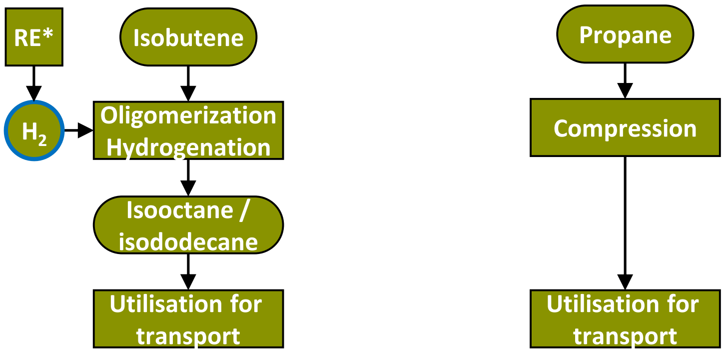

Figure 9: Conversion of gaseous intermediate products (isobutene and propane) into hydrocarbon fuels

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 (see section 3.2.2 I).

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 4.6).

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 (see also section 3.2.2 V), **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. 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).

For the present study, alternative 3 was selected.

4.7. 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:

- 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 and land use change are taken into account (see section 3.2.2 IV).

4.8. Overview of scenarios

Table 4 lists the scenarios investigated on this study. The alternative scenarios were limited to a comparison with electric cars.

Table 4: List of scenarios for analysis in WP 5. Variations from main scenarios are highlighted in blue.

		RE used for	CO_2 source	Bioreactor	Fuel product	Reference fuel
eForFuel scenarios	**Main 1**	**Electrolyser**	**Steel plant**	**Yes**	**Propane**	**LPG**
	Main 2	**Electrolyser**	**Steel plant**	**Yes**	**Isooctane**	**Gasoline**
	Main 3	**Electrolyser**	**Steel plant**	**Yes**	**Isododecane**	**Jet fuel**
		Electrolyser	DAC*	Yes	Propane	LPG
		Electrolyser	DAC*	Yes	Isooctane	Gasoline
		Electrolyser	DAC*	Yes	Isododecane	Jet fuel
		Electrolyser	Biogenic	Yes	Propane	LPG
		Electrolyser	Biogenic	Yes	Isooctane	Gasoline
		Electrolyser	Biogenic	Yes	Isododecane	Jet fuel
		Electrolyser	Steel plant	Yes	Isooctane	1G Bioethanol
		Electrolyser	Steel plant	Yes	Isooctane	2G Bioethanol
		Electrolyser	Steel plant	Yes	Isododecane	FT# bio jet fuel
Alt. scen.	BEV	Electric car	n.a.	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 10 illustrates the various combinations of influencing parameters. The settings for the baseline scenario – marked in bold in Figure 10 – 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.

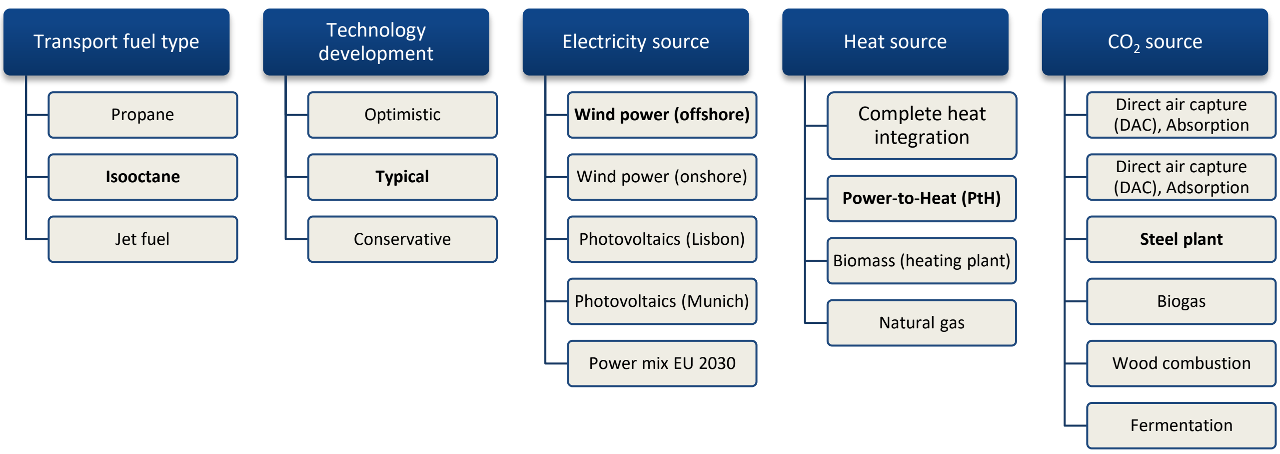

Figure 10: Influencing factors and possible settings for the analysed electro-microbial production of transport fuels. The settings of the baseline scenario are marked in bold.

5. Results

A screening life cycle assessment (LCA) was carried out for the electro-microbial production of transport fuels. For details on the methods and analysed systems see chapter 3 and 4, respectively. First, an overview of a baseline scenario (see definition in section 4.8) is given in section 5.1. Second, the effects of different scenario settings are discussed in section 5.2. Third, all scenarios are compared in section 5.3. Fourth, electro-microbial fuels are compared with other renewable transport fuels and/or power-trains (section 5.4). Finally, in section 5.5, the results are interpreted against the background of resource availability.

5.1. Baseline scenario

For the baseline scenario (see definition in section 4.8), a number of impacts categories are investigated, considering all life cycle stages. In the following, the evaluation procedure is explained on the basis of two impact categories, namely 'climate change' (characterisation factor: global warming potential, GWP_{100}) and 'land use' (characterisation factor: distance-to-nature potential, DNP). The impact categories and the corresponding LCIA methods are explained in detail in section 3.2.3.

To present the results in a clear diagram, life cycle stages are grouped. For each group, a bar section is plotted in the bar charts in Figure 11.

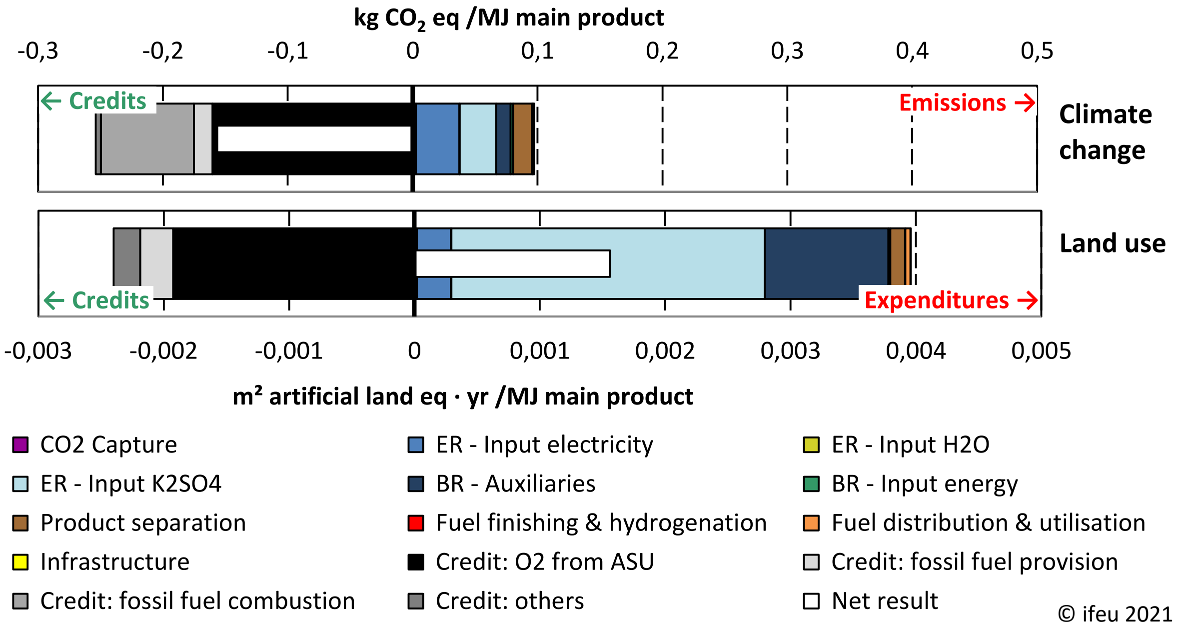

Figure 11: Greenhouse gas emissions and credits and distance-to-nature potential of the baseline scenario. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: Using the example of the impact category 'climate change' in the upper part of the graph: The bar sections on the right hand side illustrate that the production of isooctane in a process corresponding to the baseline scenario and the following usage causes GHG emissions of 0.1 kg CO_2 eq. per MJ isooctane. 0.25 kg CO_2 eq. can be saved by the production and usage of electro-microbial isooctane, most of it due to the replacement of O_2 from an air separation unit (ASU) by the co-product from the electroreactor (Credit: O_2 from ASU) and the avoidance of fossil fuel combustion (Credit: fossil fuel combustion). In summary, 0.16 kg CO_2 eq. per MJ isooctane can be saved.

When interpreting the results, attention must be paid to which life cycle stage represents the main influence of the respective group. The emissions or expenditures (resource uses) associated with the production of electro-microbial fuels are depicted on the positive axis. For the baseline scenario, the electricity use of the electroreactor (ER) and the electrolyte (K_2SO_4) make-up are the largest contributors to the impact category climate change. The K_2SO_4 make-up also contributes largely to the impact category land use, followed by the input of auxiliaries (especially nutrients) into the bioreactor (BR). The electricity and heat demand supplied by offshore wind farms contribute little to the impact category land use as the category indicator DNP currently only considers terrestrial land use. Thus only onshore distribution networks are considered. Credits due to the use of co-products and the avoided environmental burden of the supply and consumption of the corresponding fossil fuel, gasoline, are plotted on the negative axis. In this case, the credit for the co-produced oxygen (O_2) which replaces O_2 from an air separation unit (ASU) dominates both the credits for climate change and for land use. For climate change, the avoidance of CO_2 emissions during fossil fuel combustion further contributes largely to the credits. The net result is shown as a thinner white bar and is, for the baseline scenario, negative in case of climate change and positive in case of land use. This means that electro-microbially produced fuel leads to net GHG emission savings but at the same time to a net additional land use compared to the corresponding fossil fuel.

In Figure 11, the results for the impact categories 'climate change' and 'land use' are expressed in kg CO_2 eq. and m^2 artificial land eq. · yr, respectively. To make impact categories comparable, the results are normalised to inhabitant equivalents (IE) in Figure 12.

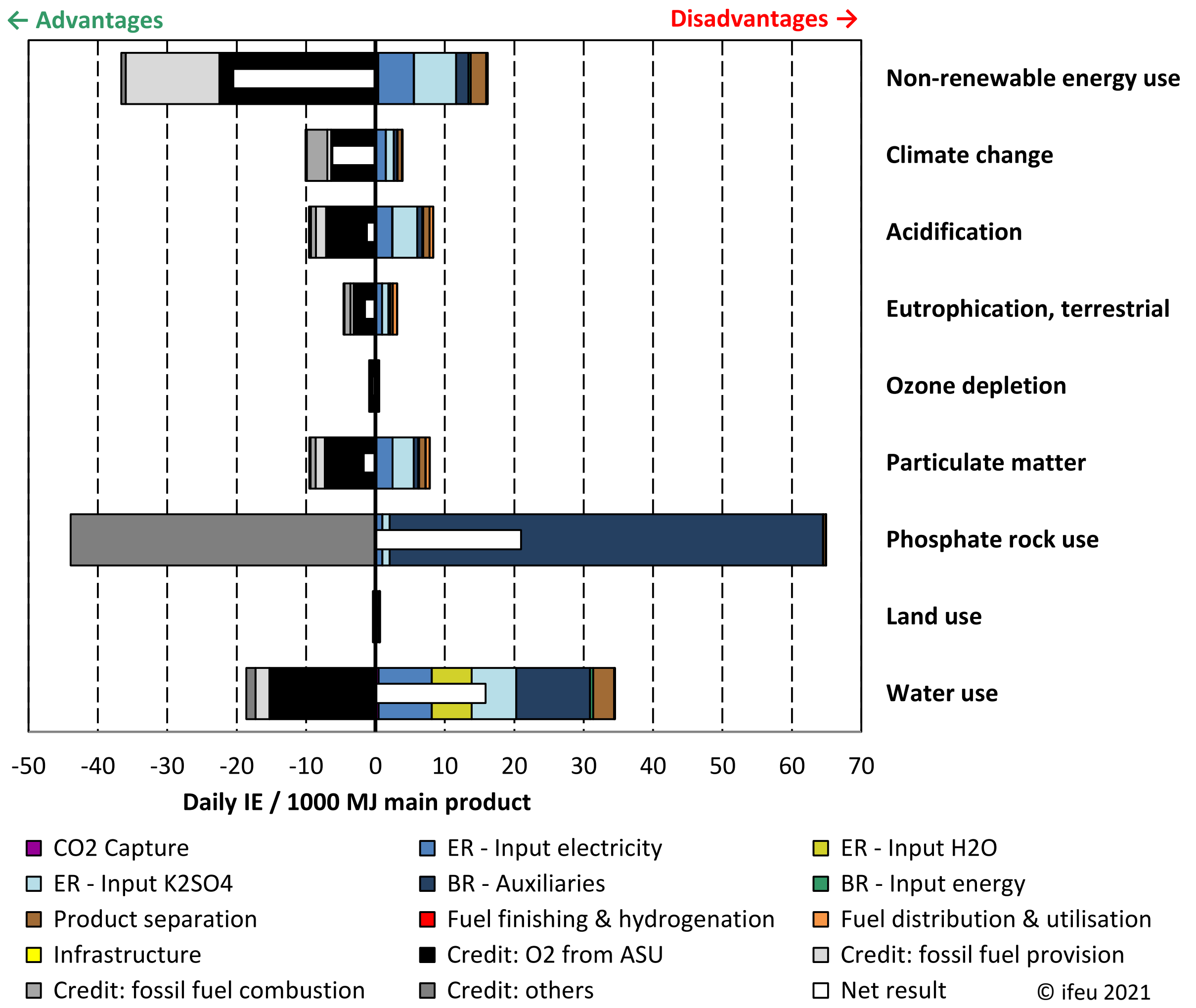

Figure 12: Normalised LCA results (given in inhabitant equivalents (IE)) for all impact categories for the baseline scenario. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 2nd bar corresponds to the GHG emissions and credits shown in Figure 11 normalised to daily inhabitant equivalents. The bar sections on the right hand side 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.

Figure 12 reveals that for the baseline scenario, the advantages clearly outweigh the disadvantages for the impact categories 'non-renewable energy use' and 'climate change'. 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 'land use', this finding contradicts at first glance the result from Figure 11. However, it should be noted that both the expenditures and the credits in this category are very small.

Life cycle stages contribute to the results to (slightly) different degrees depending on the impact category (Figure 13). The only real exception is the phosphate rock footprint. It is dominated by the nutrients required for the bioreactor and is offset by the credit for using the bioreactor sludge as fertiliser.

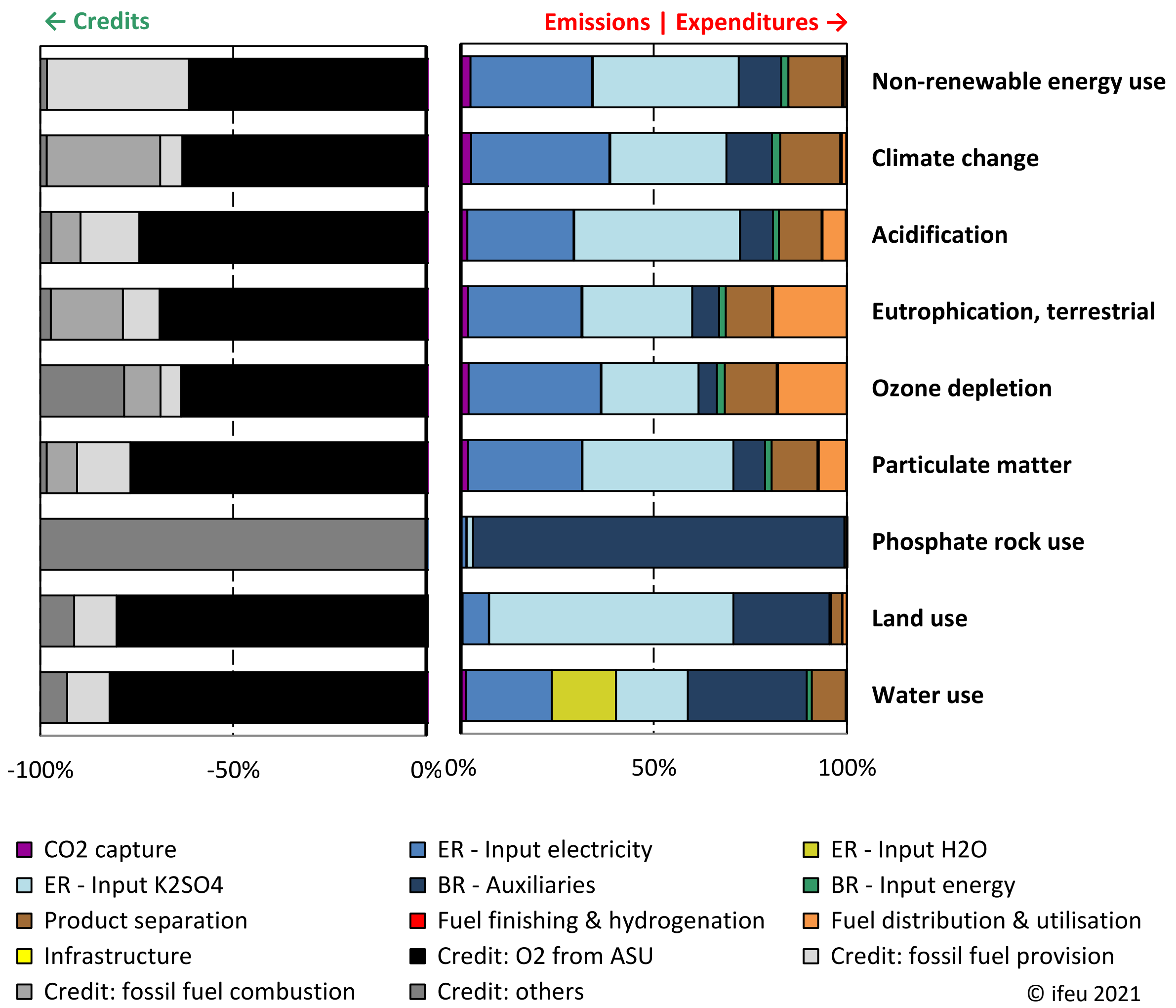

Figure 13: Dominance analysis for all environmental impact categories for the baseline scenario. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.

Although the impact categories can be influenced by different life cycle stages and the sign of their net result can differ, the trends observed when comparing different scenarios are similar for all of them. In the following, we therefore discuss the effect of different scenario settings using the impact category 'climate change' as an example. The other impact categories are only presented in case of deviating trends.

Key findings:

- Electro-microbial fuels show advantages or disadvantages compared to fossil fuels
- Life cycle stages contribute to the results of each impact category to (slightly) different degrees.

5.2. Sensitivity analyses

In this section, the effects of different scenario settings are discussed.

5.2.1. Transport fuel type

Besides an isooctane-rich mixture replacing gasoline (baseline scenario), propane or an isododecane-rich mixture can be produced to substitute liquefied petroleum gas (LPG) and jet fuel, respectively (compare Section 4.4). Figure 14 depicts the LCA results for the three different types of electro-microbially produced transport fuels (compared to fossil fuels) for the impact category 'climate change'.

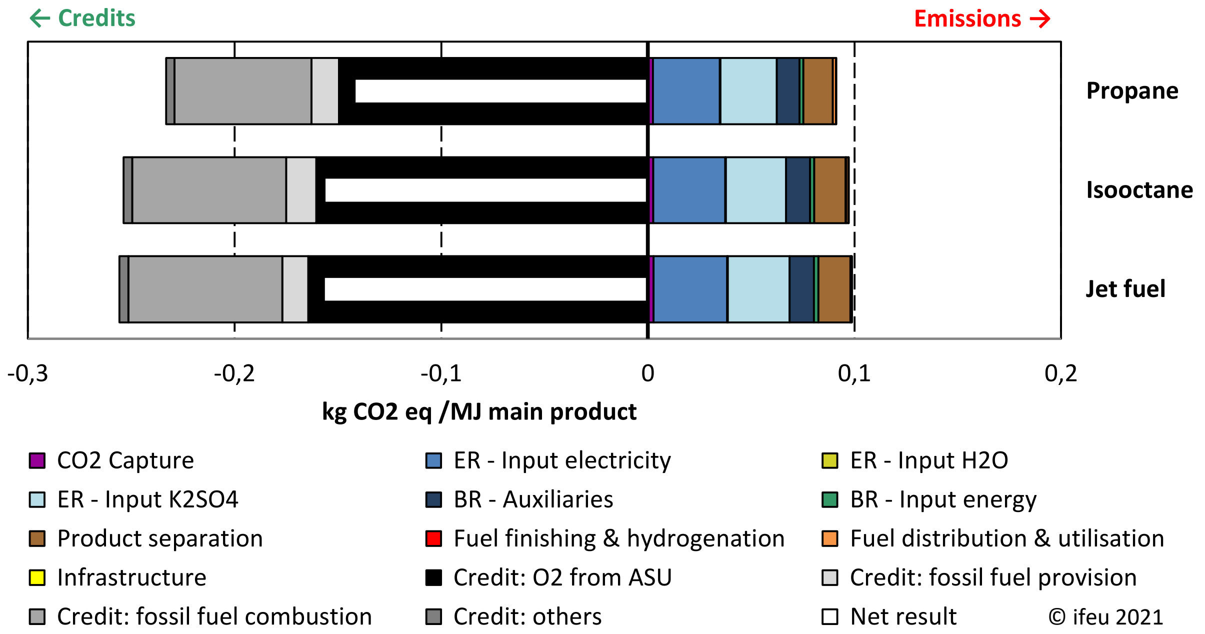

Figure 14: Greenhouse gas emissions and credits associated with the production of various transport fuels via CO_2 electrolysis. Technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 2nd bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the other bars, the fuel type was varied.

For the presented scenarios, greenhouse gas emission credits are similar for the isooctane and jet fuel routes and exceed the credits for the propane route. The differences are mainly caused by a difference in the heating value of the substituted fossil fuels. LPG has the highest heating value in terms of carbon content, so its combustion releases the least CO_2 per MJ. Similarly, emissions per MJ increase slightly with increasing chain length of the product (propane: C_3H_8; isooctane C_8H_{18}; isododecane: $C_{12}H_{26}$) for expenditures that scale with the amount of fuel produced. This is the case for the largest contributions, electricity and K_2SO_4 make-up for the electroreactor. Fuel finishing and hydrogenation, which differ technically for the different routes, have little impact on the greenhouse gas (GHG) balance. Overall, the net result of the GHG balance of the three transport fuels via CO_2 electrolysis is in the same order of magnitude. Consequently, the following analyses are conducted for isooctane.

Key findings:

- Credits and emissions of greenhouse gas per MJ transport fuel increase slightly with increasing chain length of the produced fuel
- Net result for the impact category climate change is of the same order of magnitude for the three investigated electro-microbially produced transport fuels

5.2.2. Credit for oxygen from electroreactor

In the baseline scenario, the O_2 produced at the anode is used to oxidise the CO and H_2 produced at the cathode, since the reaction products CO_2 and H_2O can be recycled into the electroreactor. The remaining O_2 could be sold as a substitute for O_2 from air separation units (ASU) which would lead to a credit in the LCA. However, it depends on future market developments whether this credit can be given. Thus, Figure 15 depicts the LCA results for electro-microbially produced transport fuels compared to fossil fuels with and without the credit for O_2.

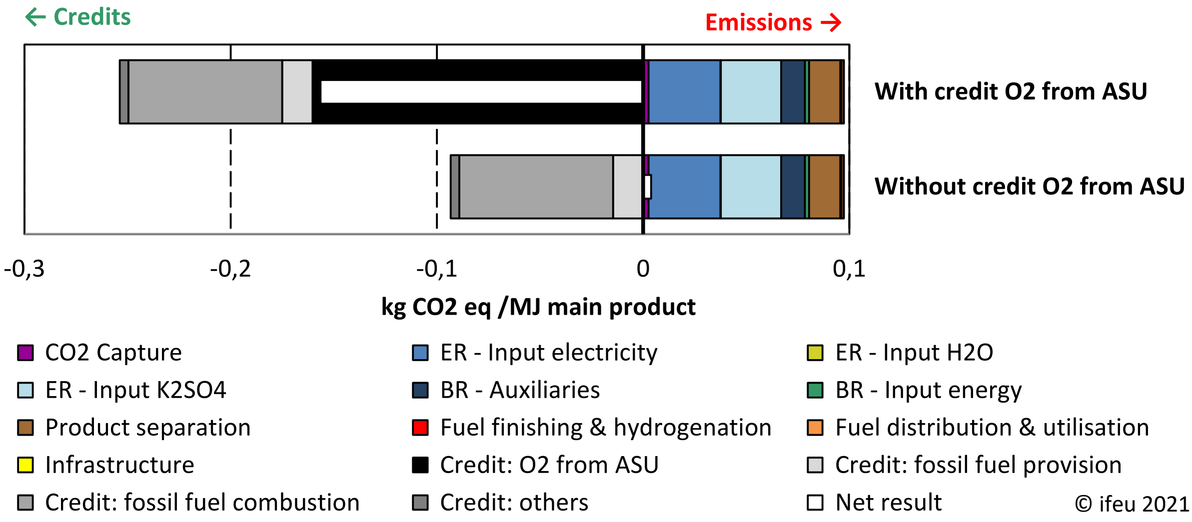

Figure 15: Greenhouse gas emissions and credits attributed to isooctane production via CO_2 electrolysis compared to fossil gasoline. The credit for O_2 from the electroreactor is omitted compared to the baseline scenario. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 1st bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the 2nd bar, the credit for O_2 from the electroreactor (credit: O_2 from ASU) is set to 0.

Figure 15 reveals that the GHG balance for electro-microbial fuels is favourable only if the O_2 produced at the electroreactor's anode receives a credit for the substituted O_2 from ASU. Without this credit, the GHG emissions are comparable to the savings from fossil fuel replacement. However, the credit can only be fully given if the future O2 demand matches the amount of O_2 produced and no other cheap renewable O_2 source is available. A steel plant, e. g. ArcelorMittal's steel plant in Ghent, consumes O_2 on a scale comparable to that of one 1 GW electroreactor (see Table 5 in section 5.5). However, the water electrolysis market is expected to grow significantly, producing huge amounts of O_2. Therefore, a full credit for O_2 (replacing O_2 from ASU) has to be critically questioned. Conversely, the overall system should be significantly optimised to achieve a positive GHG balance even without this credit.

Key findings:

- Without a credit for O_2, the production and use of electro-microbial fuels shows no clear advantages over fossil fuels.
- The process should be optimised to achieve a positive GHG balance even without this credit.

5.2.3. Technology development

The processes developed within the scope of the eForFuel project feature immature technology readiness levels (TRL), mainly TRL 4 and TRL 5. However, the LCA is conducted for scenarios representing mature technology on industrial scale ('nth plant'), as explained in section 3.1.2. To accommodate the inherent uncertainty regarding possible future technology developments, value ranges from 'optimistic' via 'typical' to 'conservative' are used. Figure 16 illustrates the LCA results for electro-microbially produced isooctane for the impact category 'climate change'.

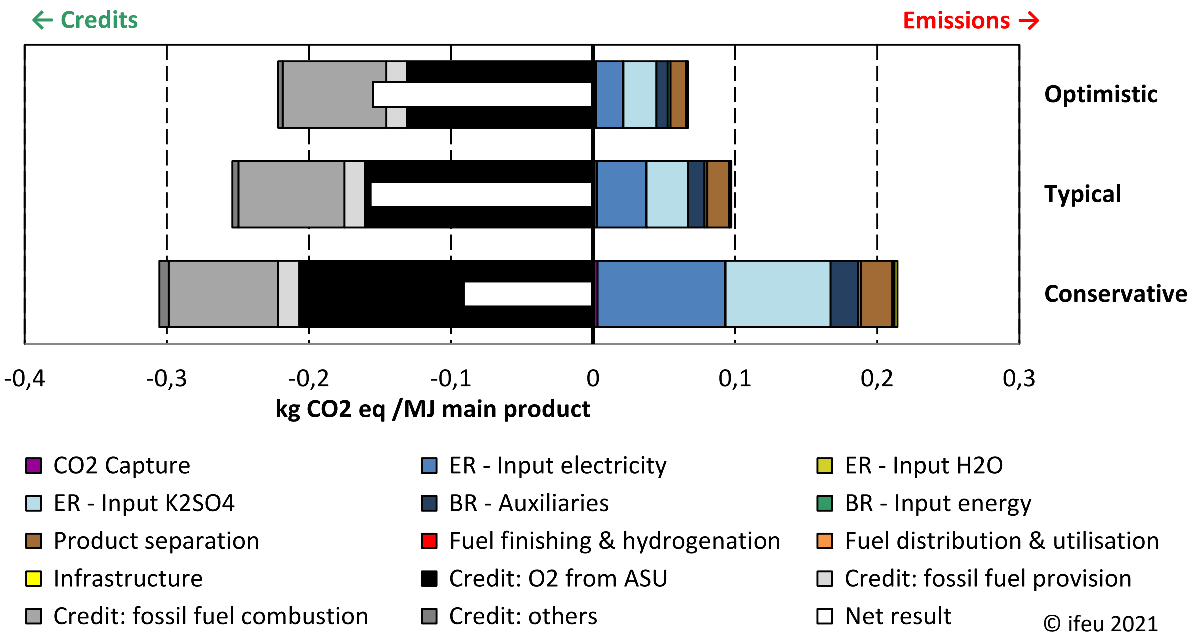

Figure 16: Greenhouse gas emissions and credits associated with the production of isooctane via CO_2 electrolysis applying 'optimistic' via 'typical' to 'conservative' values. Transport fuel type: isooctane; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 2nd bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the other bars, the values for estimating the future developments were varied.

The main life cycle stages with the largest relative change and thus uncertainty are the electricity demand of the CO_2 electrolysis and the K_2SO_4 recovery. Moreover, the credit for O_2 from the electroreactor varies considerably and has a large impact on the overall balance. The credit for O_2 is examined more closely in section 5.2.2. In summary, the net result for the optimistic scenario is slightly better than for the typical one. For the conservative scenario, the GHG balance is considerably worse but still favourable in case of electricity supply by offshore wind, heat supply by power-to-heat and a credit for O_2 produced at the anode.

Key findings:

- The GHG balance is favourable for all possible future technology development scenarios in case of electricity supply by offshore wind, heat supply by power-to-heat and a credit for O_2 produced at the anode.
- Optimising the electricity demand of the electrolysis and the K_2SO_4 recovery holds the greatest potential to improve the GHG balance.

5.2.4. Electricity source

Electricity use for electro-microbial fuels ranges between 4 MJ / MJ fuel and 24 MJ / MJ fuel, depending on the technology development scenario. In addition, a heat demand of 2 MJ / MJ fuel to 4 MJ / MJ fuel must be met by renewable energy, e.g. power-to-heat. To evaluate the impact of different electricity sources, Figure 17 shows the GHG emissions associated with electro-microbial isooctane production and use compared to gasoline for different exemplary electricity sources (see Table 1 on p. 15).

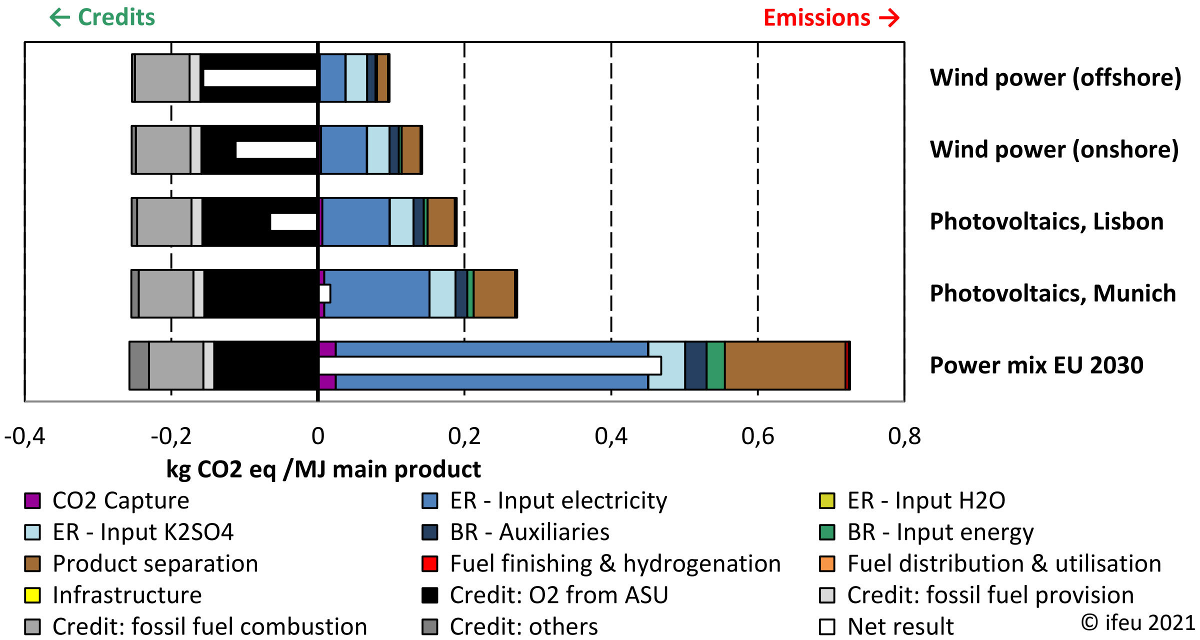

Figure 17: Greenhouse gas emissions and credits attributed to isooctane production via CO_2 electrolysis using different electricity sources compared to fossil gasoline. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 1st bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the other bars, the electricity source was varied.

GHG emissions associated with the electricity use are highly dependent on the electricity source. The same holds for the GHG emissions associated with the heat demand if – as in the presented scenario – power-to-heat (PtH) is set as the heat source. For the same reason, the credits for biogas and district heat (Credit: others) are sensitive to the electricity source. The processes with the largest energy demand are CO_2 electrolysis and product separation.

The CO_2 emission factor of the electricity used determines whether an overall favourable GHG balance can be achieved. For typical technology development, the break-even point is at ~70 g CO_2eq / kWh, but it can be as low as 30 g CO_2eq / kWh (conservative technology development). *Significant* GHG emission savings, however, can only be achieved at <15 g CO_2eq / kWh, which can currently only be realised with offshore wind power. Under a projected 2030 EU power mix, the GHG emissions are more than ten times those of offshore wind power. Consequently, this would lead to a strongly negative overall GHG balance.

Key findings:

- The overall GHG emissions are highly dependent on the electricity source. Renewable electricity is not emission-free.
- The availability of electricity sources with very low GHG emissions will determine whether electro-microbial fuels are superior to fossil fuels. Savings are only possible if 100% renewable electricity, notably wind power and PV at favourable locations, is used.

5.2.5. Heat source

To evaluate the impact of different heat sources, Figure 18 depicts the LCA results for three different types of heat sources (compared to fossil fuels) for the impact category 'climate change'.

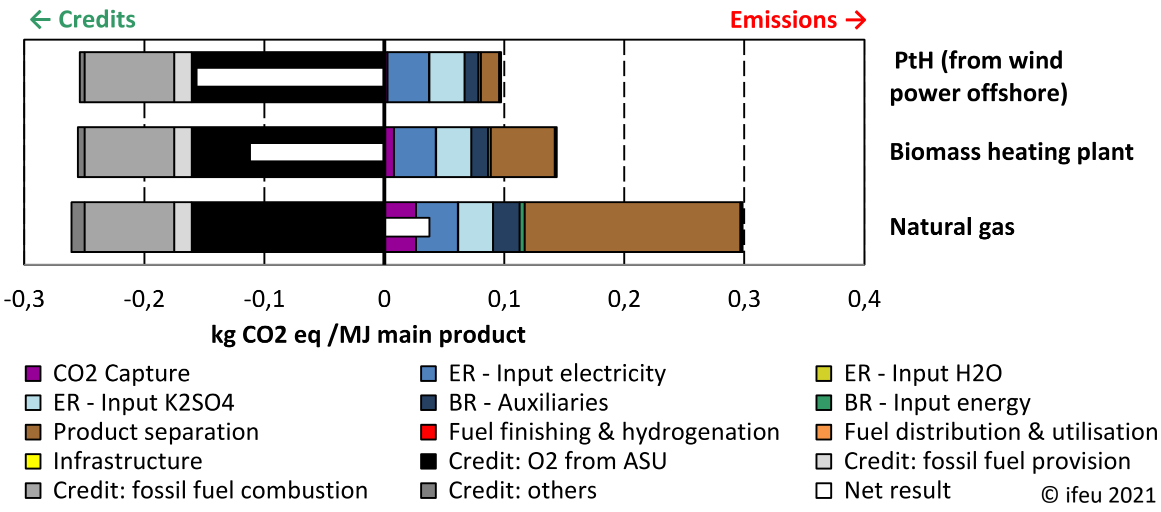

Figure 18: Greenhouse gas emissions and credits attributed to isooctane production via CO_2 electrolysis using different heat sources compared to fossil gasoline. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 1st bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the other bars, the heat source was varied.

The GHG emissions of those life cycle stages that are accompanied by a large heat use are most sensitive to a variation of the heat source. These are in particular i) product separation after the bioreactor, ii) CO_2 capture (recovery of the sorbent) and iii) thermal inactivation of the GMOs (genetically modified organisms, in BR - Auxiliaries). The credit for the combustion of biogas (Credit: others) is also dependent on the heat source, as the combustion replaces heat that would otherwise have to be provided by the respective source. On the contrary, the credit for district heat does not depend on the heat source since electricity necessary for a heat pump is replaced.

The GHG emissions and credits associated with the heat supply from a biomass heating plant are comparable to those attributed to the scenario of using power-to-heat from offshore wind farms. When using natural gas as a heat source, the emissions associated with the production of electro-microbial fuels exceed the savings. However, biomass heating plants come with considerable disadvantages regarding land use and ozone depletion potential compared to the other two options. In summary, power-to-heat combined with a renewable electricity source is the best choice from an environmental point of view.

Key findings:

- Product separation, recovery of the CO_2 capture sorbent and thermal inactivation of the GMOs require a lot of heat and lead to increased GHG emissions if the heat source is disadvantageous.
- To reduce GHG emissions, the goal in process development should be the best possible heat integration and renewable heat sources.
- Power-to-heat combined with a renewable electricity source (wind power, photovoltaics) is the best choice from an environmental point of view.

5.2.6. Heat integration and recovery

CO_2 capture, product separation and GMO inactivation require heat at mostly moderate temperatures. On the other hand, cooling is necessary for CO_2 capture, the electroreactor, product separation as well as fuel finishing and hydrogenation. For the baseline scenario, heat integration within the sub-process is assumed for CO_2 capture and product separation. Moreover, waste heat (unavoidable heat generated as co-product in industrial installations) from the electroreactor, product separation as well as from fuel finishing and hydrogenation is set to replace an ambient temperature heat source of a heat pump that feeds into a district heating network. Thus, electricity is saved and credited to the electro-microbial fuels. Cross-process heat integration and potentially even heat integration with external processes at a Verbund site is conceivable. Figure 19 shows the GHG emissions of isooctane produced in the baseline scenario, in a complete heat integration scenario and in a scenario without a credit for heat recovery compared to the corresponding fossil fuel gasoline.

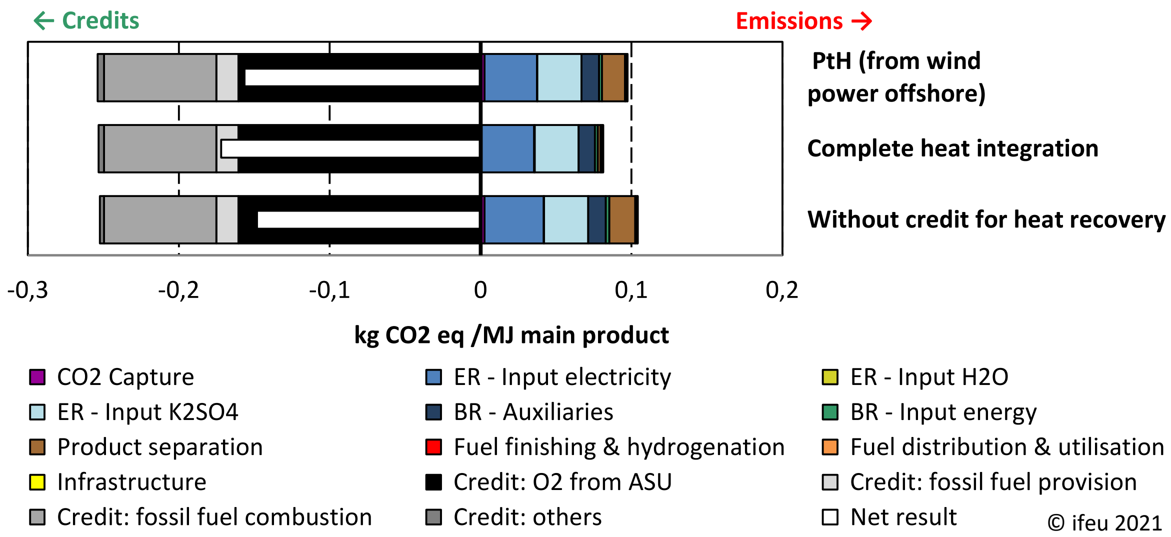

Figure 19: Greenhouse gas emissions and credits attributed to isooctane production via CO_2 electrolysis compared to fossil gasoline. Transport fuel type: isooctane; technology development: typical; electricity source: wind power (offshore); heat source: power-to-heat; CO_2 source: blast furnace gas from steel plant.
How to read the figure: The 1st bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the 2nd bar, complete heat integration is set, for the 3rd bar the credit for waste heat replacing the ambient heat source of a heat pump feeding into the district heating network is set.

As Figure 19 illustrates, complete heat integration can save 0.02 kg of CO_2 equivalents per MJ fuel compared to the baseline scenario. Especially in the case no credit is given for O_2 from ASU, this measure can decide on whether the GHG balance for electro-microbial fuels is favourable or unfavourable. The largest contributor to this saving is product separation. Since heat integration within the product separation is already included in the baseline scenario, cross-process heat integration or heat integration with another process at a Verbund site is necessary for achieve the respective savings. However, it should be noted that the product separation is modelled based on a process optimised for a biomass fuel production and is thus subject to relatively large uncertainties (see section 5.2.2). For CO_2 capture from blast furnace gas of a steel plant, heat can be provided by the steel plant.

Key findings:

- In case O_2 from ASU cannot be credited, heat integration and recovery can decisively affect the overall GHG balance result.
- To save operating costs and CO_2 emissions, heat integration is highly recommended wherever possible and economically viable.

5.2.7. CO_2 source and capturing technology

In the baseline scenario, CO_2 is captured by chemisorption in aqueous monoethanolamine (MEA) solution from blast furnace gas originating from a steel plant. The baseline scenario is compared to scenarios that use other CO_2 sources or capturing methods. In addition to other point sources like a bioethanol plant, biomethane production and wood combustion, direct air capture (DAC) is considered. From point sources with CO_2 concentrations from 15% to 40%, CO_2 is also captured by an aqueous MEA solution. The CO_2 concentration in the offgas of a bioethanol plant is close to 100%. Thus, no separation is needed in this case. For DAC, due to immature technology development, the projected 2030 process parameters of two different promising technologies are considered, namely low-temperature solid adsorption and high-temperature absorption (compare section 4.5.2) Figure 20 shows the LCA results for electro-microbially produced isooctane (compared to gasoline) for the impact category ‘climate change’.

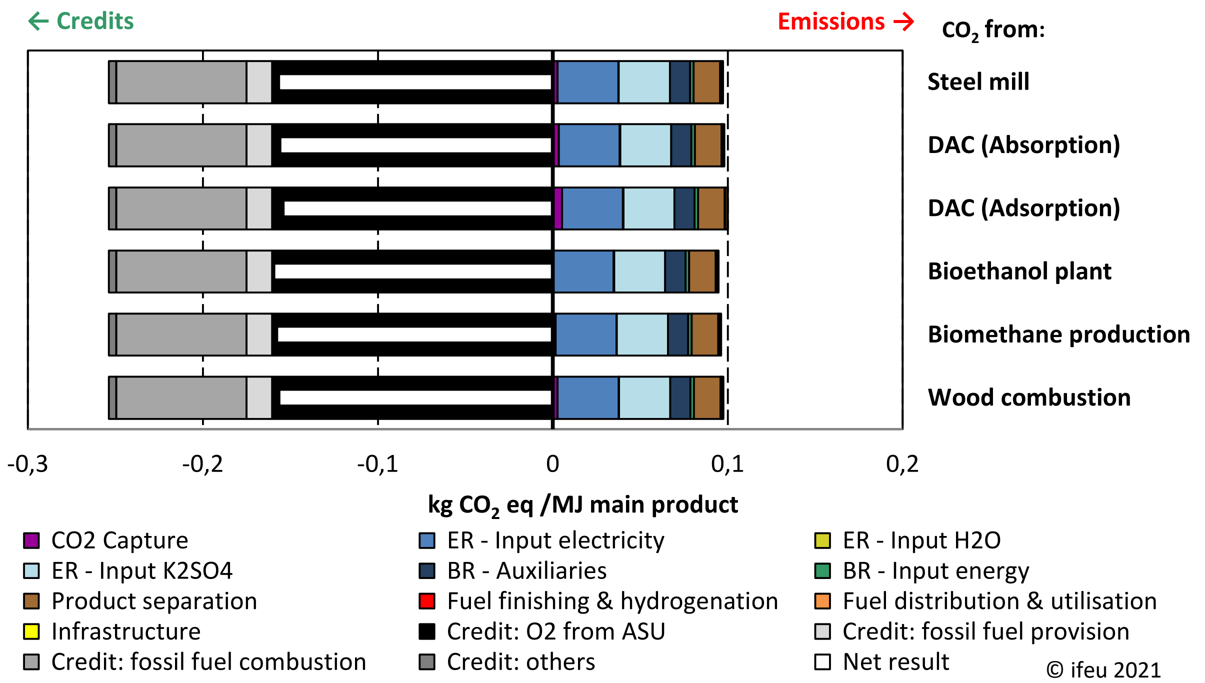

Figure 20: Greenhouse gas emissions and credits attributed to isooctane production via CO_2 electrolysis using different CO_2 sources and capturing technologies compared to fossil gasoline. Transport fuel type: isooctane; technology development: typical; Electricity source: offshore wind; heat source: power-to-heat.
How to read the figure: The 1st bar corresponds to the baseline scenario and is to be read like Figure 11, upper section. For the other bars, the CO_2 source was varied.

Compared to the contributions of other process steps of electro-microbially produced fuels, the CO_2 capture plays a minor role. The variations in the greenhouse gas balance caused by CO_2 capture are mainly due to different CO_2 concentrations in the respective gas streams and different sorption technologies. The electricity and heat demand for sorbent recovery increases with decreasing CO_2 concentration. For direct air capture, the predicted future heat and power demand of the absorptive system is slightly lower than that of the adsorptive system. In addition to the environmental impact, the amount of CO_2 available must also be considered (compare section 5.5). For the typical scenario, 17,000 t CO_2 per year are necessary which can be provided by a bioethanol plant, a steel plant, a cement plant or direct air capture.

Key findings:

- Gas streams with high CO_2 concentrations should be preferred for CO_2 capture.
- The share of CO_2 capture in total greenhouse gas emissions is low in case of power-to-heat (PtH) combined with a low-emission electricity source.

5.3. Total result range for all impact categories

Varying the settings of all influencing factors (compare Figure 10 on p. 25), a best-case and a worst-case scenario can be identified for all three transport fuel types. These settings are marked in green and red in Figure 21. In the optimistic scenario, the CO_2 source is set to be a steel plant as the other point sources cannot meet the CO_2 demand of the underlying electroreactor capacity. One of eForFuel's objectives is to use (renewable) electricity as sole energy source. Nevertheless, scenarios which involve the use of other energy sources are investigated as well. These scenarios are relevant for the evaluation of using eForFuel as a transition technology or in case of insufficient electricity and heat provision from renewables. For a potential analysis, see section 5.5. For all scenarios, credits for O_2 and waste heat recovery are considered.

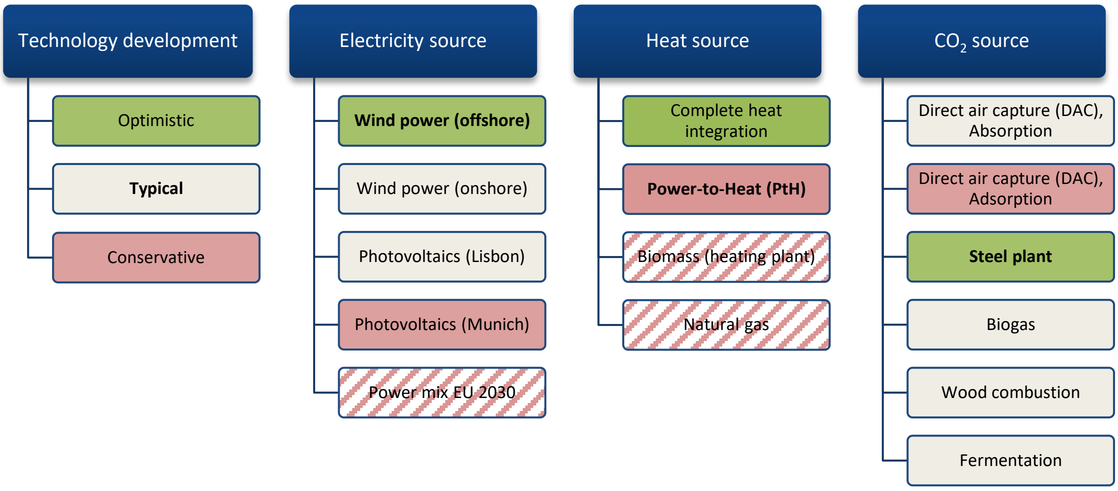

Figure 21: Influencing factors and possible settings for the analysed electro-microbial production of transport fuels. The best-case scenario is marked in green; the worst-case scenario is marked in red. Scenarios involving energy sources other than renewable electricity are shaded red.

Figure 22 presents the results of the life cycle GHG balance related to inhabitant equivalents (IE) for the best-case and the worst-case scenario for electro-microbially produced isooctane (for the scenario settings illustrated in Figure 21). The net results can be combined to a range (bar at the bottom). This procedure is performed for all impact categories and fuel types and illustrated in Figure 23.

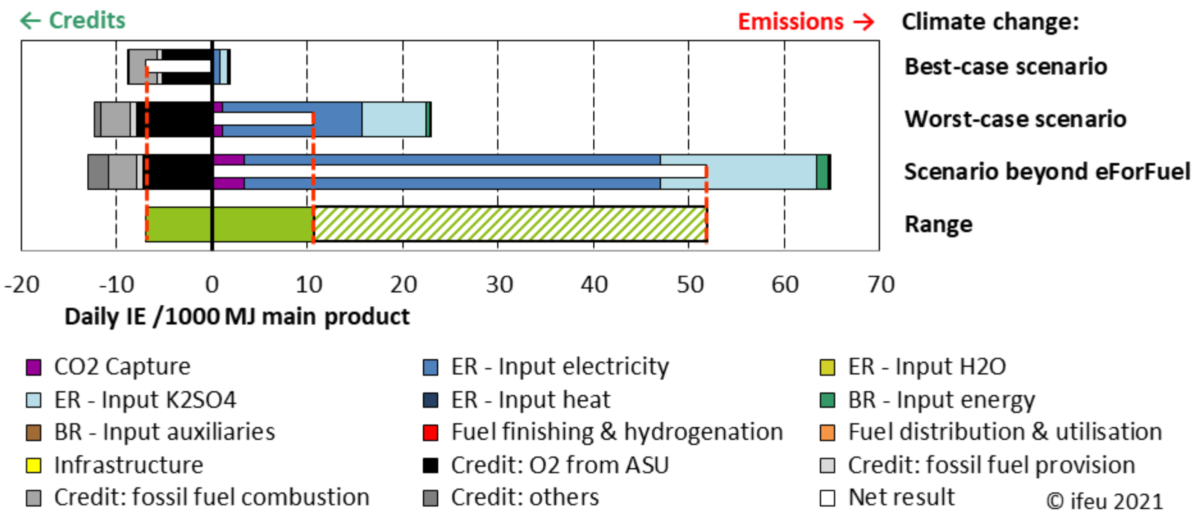

Figure 22: Normalised greenhouse gas emissions and credits of the best-case scenario (1st bar), the worst case scenario (2nd row), the scenario involving energy sources other than renewable electricity and the resulting range for electro-microbially produced isooctane (3rd row).
How to read the figure: The bar sections of the first three bars illustrate the GHG emissions, GHG credits and the overall balance from the electro-microbial production of 1000 MJ isooctane normalised to the emissions of an average EU citizen for different scenarios. Combining the best-case and worst-case scenario results in a range of possible scenarios for which the eForFuel project is aimed (4th bar, completely filled bar section). The shaded bar section of the 4th bar shows the range of possible scenarios involving energy sources other than renewable electricity.

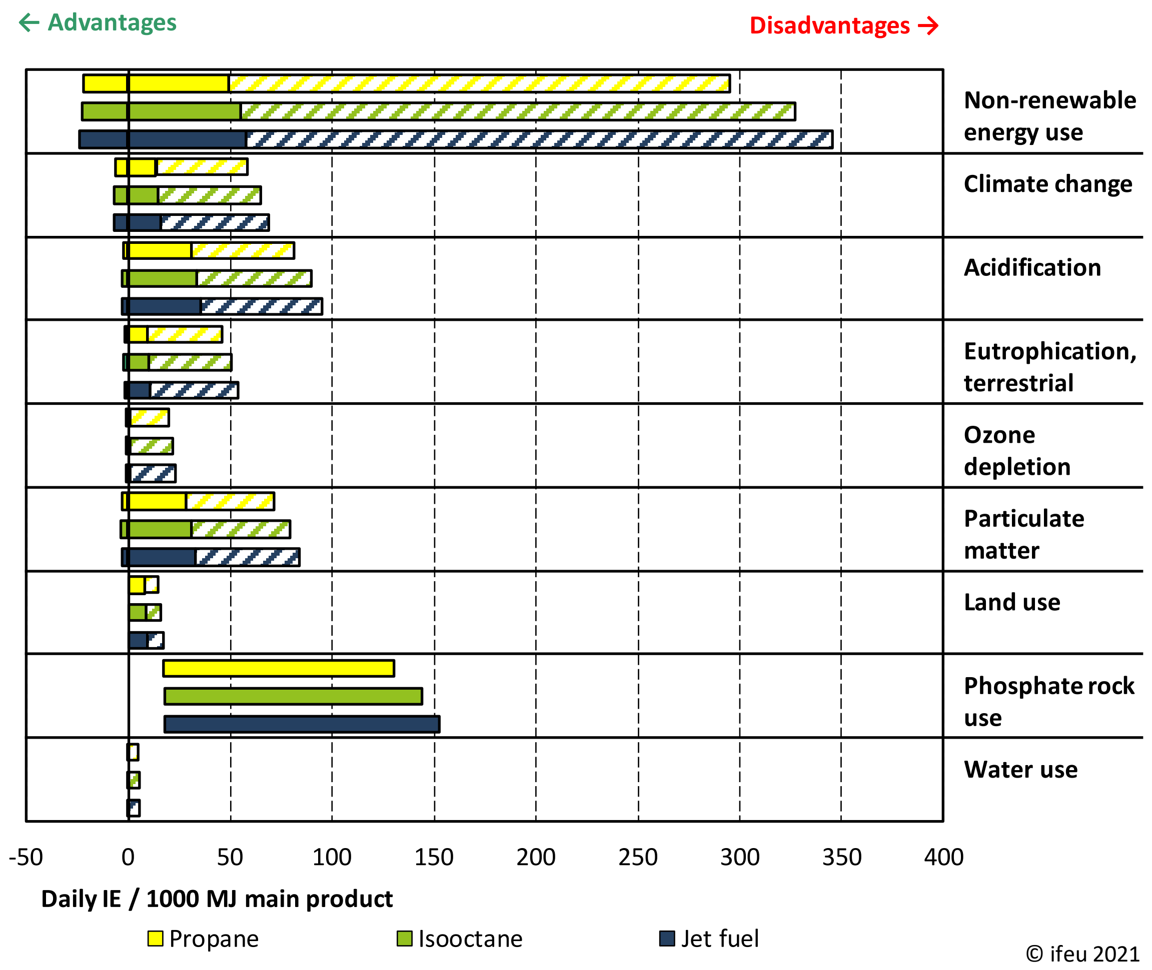

Figure 23: Ranges of normalised environmental impacts for electro-microbially produced transport fuels.
How to read the figure: All environmental impacts are normalised to daily inhabitant equivalents (IE) per 1000 MJ electro-microbially produced fuel. Different colours correspond to different fuel types. The procedure of determining the range for each environmental impact and fuel is explained in Figure 22.

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. This is also the case for the baseline scenario (compare section 5.1), as this scenario is close to 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.

Key findings:

- 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.

5.4. Comparison to other renewable transport fuels and/or power-trains

To interpret the results, electro-microbial fuels are compared to other renewable fuels and power-trains. The scenarios defined in section 5.3 (best-case, worst-case, energy sources other than renewable electricity) are used for the evaluation of electro-microbial fuels. For the alternatives, the range of advantages or disadvantages compared to fossil fuels results from technology and resource variation, which is explained in detail for each fuel type.

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 24 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.

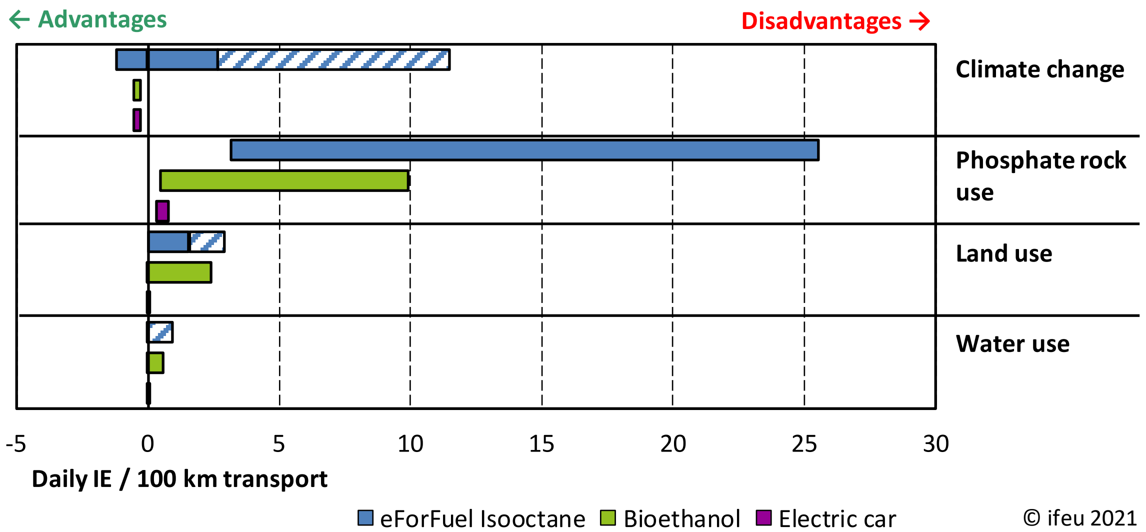

Figure 24: Comparison of electro-microbially produced isooctane to bioethanol and electric cars for different impact categories. The environmental impacts are normalised to daily inhabitant equivalents per 100 km transport.
How to read the figure: The first three bars show the range of GHG emissions 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.

As the technology development of e-fuels is more uncertain than for bioethanol-driven and electric cars, the range for the two latter alternatives is narrower than for the former. 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.

An alternative to electro-microbial **propane** are electric cars. Figure 25 compares the range of environmental impacts of these two alternatives. The range for electric cars is caused by different sources of electricity. The results for the comparison of electro-microbial propane with electric cars are similar to the results for isooctane.

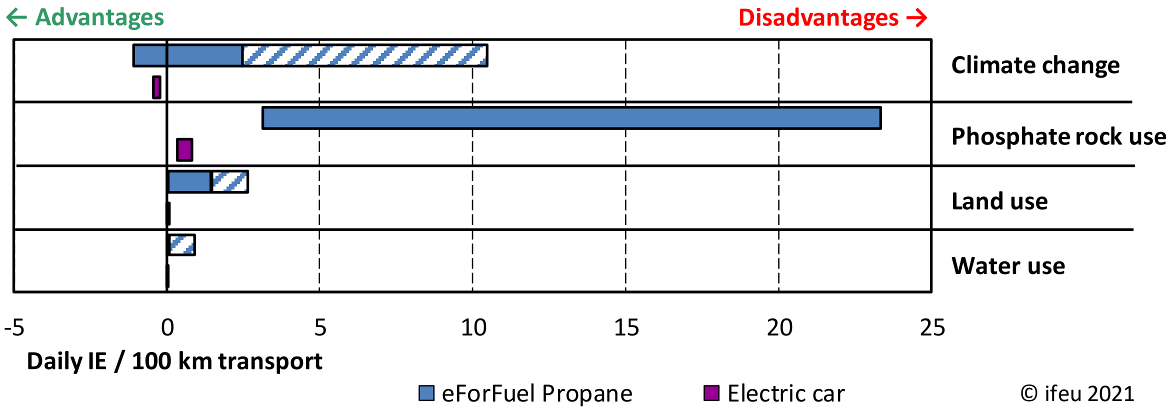

Figure 25: Comparison of electro-microbially produced propane to electric cars for different impact categories. The environmental impacts are normalised to daily inhabitant equivalents per 100 km transport.
How to read the figure: The first two bars show the range of GHG emissions and credits associated with a 100 km trip in a car powered by electro-microbial propane or a rechargeable battery, each compared to a car powered by LPG. For example, the 2nd bar indicates that the use of an electric car saves GHG emissions equivalent to 0.3 to 0.5 daily emission amounts of an average European citizen.

Electro-microbial **jet fuels** are compared to the alternative Fischer-Tropsch bio jet fuels. Figure 26 compares the range of environmental impacts of these two alternatives. The range for Fischer-Tropsch bio jet fuels is caused by different sources of electricity and heat. The results for the comparison of electro-microbial propane with electric cars are similar to the results for isooctane.

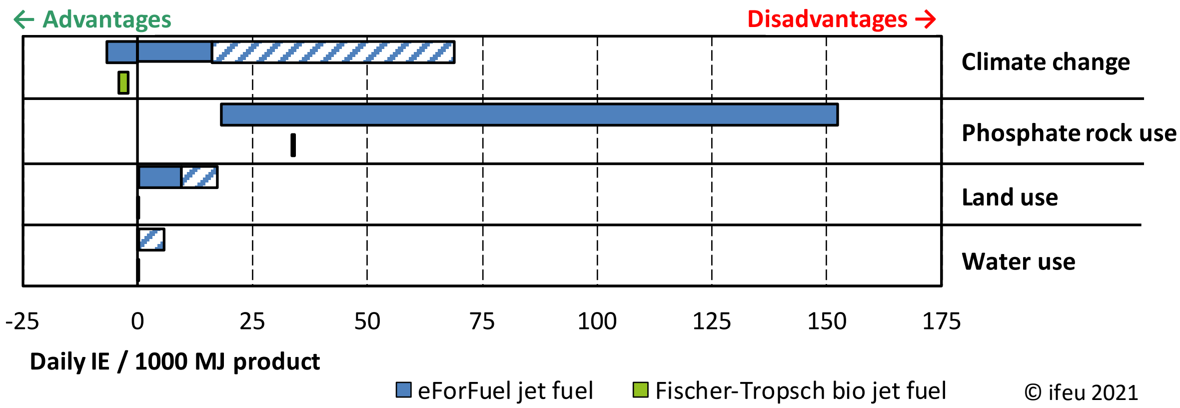

Figure 26: Comparison of electro-microbially produced isododecane to Fischer-Tropsch bio jet fuel for different impact categories. The environmental impacts are normalised to daily inhabitant equivalents per 1000 MJ product.
How to read the figure: The first two bars show the range of GHG emissions and credits associated with the use of 1000 MJ electro-microbial jet fuel (isododecane) or Fischer-Tropsch bio jet fuel in an aircraft, each compared fossil jet fuel. For example, the 2nd bar indicates that the use of Fischer-Tropsch bio jet fuel saves GHG emissions equivalent to 2 to 4 daily emission amounts of an average European citizen.

Key findings:

- In the best-case scenario, electro-microbial fuels perform better than renewable alternatives in the category ‘climate change’.
- In the use of phosphate rock, renewable alternatives may be superior to electro-microbial fuels.
- For worst-case scenarios, the environmental impacts of electro-microbial fuels are similar or worse than for bioethanol fuels or electric cars.
- The eForFuel technology should not be combined with non-renewable energy supply, since environmental impacts are considerably worse than alternatives using the same energy mix.

5.5. Perspectives

Table 5 shows the calculated inputs (CO_2 and electricity) and outputs (O_2 and isooctane) for the three electroreactor (ER) capacities considered in this project, as well as the area required for renewable electricity provision.

Table 5: Demand and output of relevant resources and products for electroreactors studied in the different scenarios.

Technology development	Power ER [MW]	CO_2 demand [t/year]	Electricity demand [PJ/year]	Area for wind park [km²]	Area for PV system [km²]	Output O_2 [t/year]	Output isooctane [t/year]
conservative	20	$1.1 \cdot 10^3$	0.21	2.8 - 10.6	0.8 - 1.2	$1.4 \cdot 10^3$	$0.17 \cdot 10^3$
typical	100	$17 \cdot 10^3$	1.5	20.7 - 77.5	5.5 - 8.6	$21 \cdot 10^3$	$3.3 \cdot 10^3$
optimistic	1,000	$0.36 \cdot 10^6$	22	304 - 1,140	82 - 127	$0.42 \cdot 10^6$	$82 \cdot 10^3$

Input-related potentials

The CO_2 and electricity demand is dependent on the technology development scenario and the corresponding electroreactor (ER) capacity. In an optimistic scenario, a 1 GW ER would have an electricity demand which would require an offshore wind farm covering an area of 304-1,140 km² or a PV plant covering 82-127 km². For comparison, the world's currently largest operational offshore wind farm "Hornsea 1" (1.2 GW) covers an area of 407 km². However, land area is a scarce resource in densely populated Europe. The same applies to marine areas suitable for offshore wind parks.

In terms of CO_2 demand for a 1 GW ER (360,000 t CO_2/year), only larger point sources of fossil CO_2 emissions such as the cement, iron and steel and chemical industry come into question. For comparison, ArcelorMittal's steel plant in Ghent emitted 4.12 million t CO_2 in 2019. In a typical scenario, both electricity demand and CO_2 demand are considerably lower, the latter becoming compatible with biogenic CO_2 sources such as fermentation (bioethanol plant: 50,000 - 150,000 t CO_2/year) or anaerobic digestion (biomethane plant: 1,000 – 10,000 t CO_2/year).

Output-related potentials

Like the inputs, also the outputs of oxygen (O_2) and electro-microbial fuel depend on the technology development scenario. In an optimistic scenario, 420,000 t O_2/year would be produced. This amount could only be accommodated by a large consumer such as a steel plant. Only in case the O_2 is used (and substitutes conventionally produced O_2), a credit for the avoided environmental burden can be given (see section 5.2.2).

Table 6: Final consumption of motor gasoline and gas/diesel oil for transport 2019 – by fuel (ktoe) [European Commission 2021]

	Total final consumption*	Motor gasoline	Gas/diesel oil
EU-27	**250,695.4**	66,706.5	183,988.8
EU-28	**289,049.5**	79,199.2	209,850.3
BE	**8,087.1**	1,800.7	6,286.4
DE	**50,681.2**	16,715.3	33,965.9

* Without bio components

At the same time, the electro-biorefinery would only yield 82,000 t/year of isooctane. This is a relatively meagre output, considering both the high electricity input and current fuel consumption levels in the EU (Table 6): the output of a 1 GW eForFuel electro-biorefinery would only correspond to 0.15% of Germany's total final consumption of motor gasoline and gas/diesel oil in road transport.

6. Key findings, conclusions and recommendations

6.1. Key findings

The results presented in chapter 5 can be summarised as follows differentiated in 3 subtopics:

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

I eForFuel vs. conventional fuels

The main objective of the eForFuel project was to develop processes for the production of renewable hydrocarbon fuels that are more environmentally friendly than conventional (fossil) fuels. The renewable fuels investigated are so-called electro-microbial fuels, which are produced in an electro-biorefinery consisting of an electroreactor and a downstream bioreactor. 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, the GHG balance is always negative.
- 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, which can currently only be realized with offshore wind power.

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- 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 be significantly reduced, so that the overall GHG balance may be unfavourable.

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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.

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

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.


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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.


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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. For road transport, electro-microbial fuels are therefore not a sustainable option. 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.

III 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. The following focal areas from an environmental protection point were identified and should be targeted primarily in further development:

- In the baseline scenario, the electroreactor (ER) is responsible for 60-70% of all environmental impacts (emissions or resource use), especially due to the relatively low conversion efficiencies in CO_2 electrolysis: only 50-67% of the electricity and only 36-47% of the CO_2-C are converted into formic acid. This leads, on the one hand, to an enormously high demand for renewable electricity and, on the other hand, makes costly recycling of the C-rich gases from the cathode (CO_2 and CO) necessary. Likewise, electrolyte (K_2SO_4) and water must be recycled in an energy-intensive manner via electrodialysis. These are all important starting points for optimising the ER.
- In contrast to the ER, the bioreactor (BR) itself is only responsible for a small proportion of the environmental impacts, with the exception of the phosphate footprint. However, if it is considered including product separation and purification, a different picture becomes apparent: indirectly, the relatively low C-conversion efficiency of only 4-5% (from formic acid to isobutene) and the operation of the BR with air ultimately lead to a gas mixture of at least four components (N_2, O_2, CO_2 and isobutene or propane). From this mixture, i) the low-concentration target product (isobutene or propane) and ii) the CO_2 to be recycled must be separated in a very energy-intensive two-stage process. Therefore, the conversion efficiency in the fermentation should be significantly optimised or an alternative fermentation concept should be considered.
- The use phase (fuel distribution & utilisation) makes relevant contributions in the impact categories eutrophication and stratospheric ozone depletion, and somewhat less in acidification and particulate matter. There is a need for optimisation here, but only after more fundamental aspects have been remedied.

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- Other process steps, such as the type of CO_2 source and capture technology[2] or fuel finishing & hydrogenation, are of secondary importance for most environmental impact categories. In order to be able to make such statements, it is important to analyse the entire life cycle and all environmental impacts.

6.2. Conclusions

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

- 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

[2] This statement applies to the approach taken in this study that CO_2 of non-renewable origin is considered a waste (produced as an unavoidable and unintentional consequence of a production process in industrial installations) and that the environmental burden associated with CO_2 remains with the main and co-products of the emitting process.

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.

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- Like a number of other studies, the present study shows that e-fuels are not a sustainable option for the future of road transport or for paving the way for a continued use of internal combustion engines in vehicles. 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.

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- 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.

6.3. Recommendations

On the basis of the above conclusions, the following recommendations can be made to different stakeholders from an environmental protection perspective:

To 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:

- Technical breakthroughs in the electroreactor: here it is necessary i) to actually achieve (and ideally even exceed) at least the conversion and recycling efficiencies and electrode lifetimes set out in the typical scenario in practice and ii) to exploit all potentials for heat integration, including the use of low-temperature waste heat[3]. Furthermore, alternative reactor designs (e.g. with polymeric ionic liquids) and/or other electrode materials (e.g. bismuth) should be tested. The goal would be to

[3] unavoidable heat generated as co-product in industrial installation, which would be dissipated unused in air or water

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.

- 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].


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  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

The present study shows that synthetic fuels / e-fuels / PtX fuels 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'. Moreover, 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 footprints or which are used in sectors where there are no or few other renewable alternatives. In this context, it is important to consider accompanying sustainability assessments from the outset, which can identify hot spots or optimisation potential while the process is still ongoing.

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 that requires the least electricity should be promoted. This means that there may well be markets worthy of support for formate-based concepts – but at least from the current perspective not in the transport sector/ for the production of pure energy carriers. 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.

7. Abbreviations

ASU	Air separation unit
BEV	Battery electric vehicle
BF (gas)	Blast furnace (gas)
BR	Bioreactor
CCU	Carbon Capture and Utilisation
CO	Carbon monoxide
CO2	Carbon dioxide
DAC	Direct air capture
DNP	Distance-to-nature potential
DoA	Description of Action
ER	Electroreactor
EU	European Union
FT	Fischer Tropsch
GA	Grant Agreement
GHG	Greenhouse gas
GMO	Genetically modified organism
GWP	Global warming potential
H2	Hydrogen
H2O	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
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPG	Liquefied petroleum gas
LU	Land use
LUC	Land use change
MEA	Monoethanolamine
MJ	Megajoule
MW	Megawatt
N2	Nitrogen
NREU	Non-renewable energy use
O2	Oxygen
PEM	Proton-exchange membrane, or polymer-electrolyte membrane
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)
TRL	Technology Readiness Level
WP	Work package

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