PROJECT ACRONYM

eForFuel

PROJECT TITLE

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

Deliverable 5.4

Report on socio-economic and policy assessment

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1	17/11/2021	First draft	Heiko Keller, Nils Rettenmaier, Guido Reinhardt
2	10/12/2021	Final version	Heiko Keller, Nils Rettenmaier, Guido Reinhardt

Cooperation between participants

This deliverable D5.4 “Report on socio-economic and policy assessment” has been prepared by IFEU and presents the results of its work under Task 5.4. The socio-economic assessments were performed on the basis of mass and energy flow data which were provided by MPG, b.fab, USTUTT, SINTEF, UA and GBE. Prices were provided by AM (Task 5.3) and BFC contributed their results of the public perception survey (D6.6) conducted under Task 6.1.

All partners contributed to this deliverable by revising and improving the content of the whole document.

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Social Implications of Electro-Microbially Produced Transport Fuels

This report was produced as Deliverable 5.4 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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1. Executive summary


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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 per year until 2035 if no additional measures were implemented [EEA 2021]. Over the past 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 element of this is the socio-economic and policy assessment, which is presented here.

This report consists of two analyses: (i) an assessment of the socio-economic impacts which the implementation of the eForFuel concept can have as well as (ii) an evaluation of potential social and policy barriers to the implementation of the eForFuel concept.

Future social risks from the implementation of the eForFuel concept have been identified by means of social life cycle assessment (sLCA) using the social hotspot database (SHDB). The results show a large range of social risks associated with electro-microbial fuels according to the eForFuel concept because, among others, the efficiencies of potential mature industrial scale processes are highly uncertain. A socially beneficial implementation of these electro-microbial fuels would therefore require (i) technical improvements to reach efficiencies towards the upper end of the modelled range and thus lower demands for inputs as well as (ii) a careful monitoring and management of social risks in the supply chain. The latter should focus primarily on the hot spots originating from the renewable electricity supply as well as establishing a socially sustainable procurement of inputs such as electrolytes and fermentation media.


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If substantial electricity imports into the EU, e.g. from the Middle East and North Africa (MENA region), are considered for e-fuels, high risks would arise and therefore a risk management strategy for these countries would be the most important element to ensure socially sustainable e-fuels. Conversely, in particular a good conduct in high-risk procurement could lead to significant social benefits because having decent jobs and additional income is particularly important in this region. In order to seize this opportunity and adequately address the risks, a reliable cooperation at equal level requires political initiatives. This is just one of many projects for which the future depends on a concept for a reliable, competitive and socially beneficial provision of renewable electricity.

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If managed diligently, the overall social impacts of renewable electricity provision and its use for the production of e-fuels can be positive despite the risks that are identified by the sLCA methodology. The benefits: industrial installations which produce electro-microbial fuels according to the eForFuel concept provide a number of jobs in the installations themselves and more so in supply industries. If e-fuels replace crop-based biofuels, social risks in those fuel supply chains would be mitigated. In order not to cause similar risks elsewhere, however, the efficiencies in the production of the analysed electro-microbial fuels have to be highly optimised. Furthermore, e-fuels can provide for socially beneficial transportation needs in a climate-neutral world. Nevertheless, transportation that does not contribute to well-being should be reduced as far as possible.

A future production of e-fuels will not only have social implications; vice versa, society can also support or inhibit their realisation. At present, public perception appears to be neutral but is also characterised by a lack of detailed knowledge. This could quickly change since debates in the media on the role of e-fuels are likely to increase. Therefore, it is important for eForFuel to develop a communication strategy which highlights the strengths of the concept but also avoids greenwashing the concept.

The market acceptance of the e-fuels is expected to be dominated by price and technical compatibility, in particular with regard to jet fuels. Priority market targets should be marine and aviation fuels that are hardest to replace by direct electrification.

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The most significant barriers from social systems to implementation arise from the legal uncertainties, which is due to still pending legislation in the context of the Renewable Energy Directive (RED II). In order to ensure that pending delegated acts support a sustainable future of e-fuels, it is crucial to avoid regulatory gaps between the EU emissions trading system (ETS) Directive (Directive 2003/87/EC) and the RED II. Otherwise existing CO_2 emissions could remain unaccounted for in both delivering sectors such as the steel, cement and chemical industry and in the receiving fuel sector and thus escape regulation.

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

Key deliverable achievements:

1. Assessment of potential social risks and benefits associated with a future implementation of the eForFuel concept was successfully conducted; hot spots were identified.
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. Analysis of potential social and policy barriers towards a future implementation of the eForFuels concept conducted including public perception, market acceptance as well as the regulatory framework and policies.
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 (**Fehler! Ungültiger Eigenverweis auf Textmarke.**). 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.

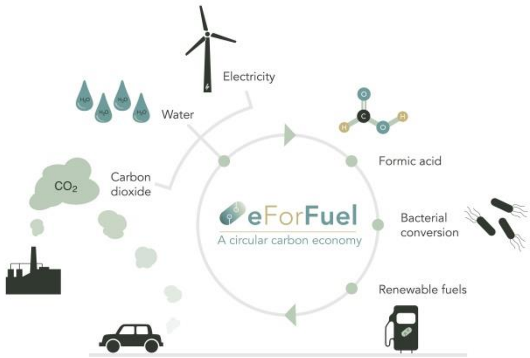

Figure 1: The eForFuel concept

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 socio-economic and policy life cycle assessment' (Deliverable D 5.4) covers the analysis of social impacts along this life cycle. Together with the 'Report on life cycle assessment' (Deliverable D 5.2) and the 'Report on techno-economic assessment' (Deliverable D 5.3), it forms the foundation for the subsequent integrated sustainability assessment. The main goal of this report is to assess the potential social risks associated with the implementation of the eForFuel concept in the future. Methodological details are summarised in chapter 3, followed by a description of the analysed systems in chapter 4. Results are presented in chapter 5 and 6. The report closes with conclusions and recommendations in chapter 7.

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 socio-economic and policy 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 work package 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 socio-economic and policy 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, European Commission 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.

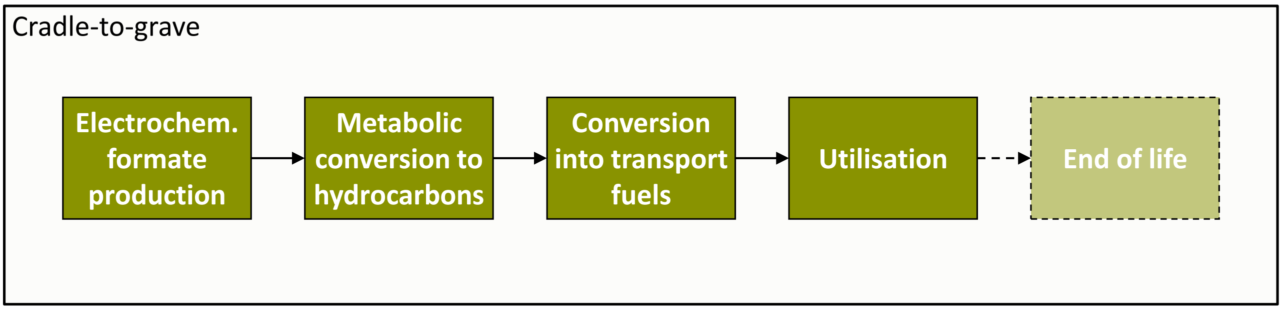

Figure 2: System boundary (cradle-to-grave) applied within the eForFuel project.

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 chosen because of project partner ArcelorMittal's steel plant in Ghent.

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 were 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 Description of Action, 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 sLCA

Social life cycle assessment (sLCA) is based on the life cycle thinking approach like environmental LCA. For that reason, many provisions from international environmental LCA standards [ISO 2006a; b] and the common definitions and settings described in section 3.1 can be and are applied to this sLCA study, too. The methodology of this sLCA study follows the guidelines for social life cycle assessment of products and organizations[Benoît Norris et al. 2020]. Several specific settings and methodological choices nevertheless have to be made for each individual study based on this methodology. In the following, these choices are detailed.

- Choice of assessment approach:
  The impact assessment method chosen is the Reference Scale Assessment (RS). This method classifies observed social risks of activities related to a product system e.g. as low, medium or high compared to a reference scale. This classification can be based on international standards, local laws or industry best practices – but also on other documented criteria [Benoît Norris et al. 2020]. In this study, the social risks observed in a specific industrial sector in a specific country are classified into the social risk levels 'low', 'medium', 'high' and 'very high' for each indicator using the criteria as described by [Benoît Norris et al. 2019a]. This allows to estimate the magnitude and significance of the potential social impacts associated with a product system. The alternative method Impact Pathway Assessment, which was not chosen for this study, uses causal or correlation/regression-based directional relationships between the product system/organizations activities and the resulting potential social impacts [Benoît Norris et al. 2020]. This approach is not as mature as the reference scale approach yet.

- Background database:
  Background data on social risks are taken from the Social Hotspot Database (SHDB, version 2019 (V4) [Benoît Norris et al. 2019a]), which is based on the multiregional input/output (MRIO) model GTAP version V9 (reference year 2011).

- Activity variable
  Observed social risks, which were classified using the reference scale approach, are related to an activity variable to allow a connection to a product system. As activity variable work-hours in the individual country-specific sector have been chosen following the approach of the SHDB. This reflects the labour intensity of a production activity. The activity variable is multiplied by a factor associated with the social risk levels of an indicator in a country-specific sector to calculate the

medium risk work-hours equivalent. In this project, the factors proposed by [Benoît Norris et al. 2019a] are used.

- Indicators, impact categories, weighting and aggregation
  The aim of sLCA is to depict potential social impacts, i.e. potential impacts on the well-being of stakeholders/affected persons. These impacts are estimated using the full set of 141 risk indicators grouped into 24 subcategories or 5 impact categories (‘labor rights and decent work’, ‘human rights’, ‘health and safety’, governance’ and ‘community’) provided by the SHDB [Benoît Norris et al. 2019 p. 11]. Values of related indicators are averaged to yield an impact subcategory value. Aggregation of subcategory values to category values and/or of subcategory values into a single risk score using the unit “medium risk work-hours eq.” requires weighting factors. Weighting of largely independent social impacts is necessarily based on value-based choices. For social impacts this is even more difficult than for environmental impacts because each affected person has its individual set of preferences. Data for an alternative normalisation approach is not available. For the purpose of displaying all impact subcategories values in the same graph, they are weighted equally. This allows identifying social hot spots but no further conclusions on severity of potential impacts or on trade-offs like the reduction of one risk at the cost of increasing another one.

Choices specific for the assessed system:

- Data on background system:
  The mass and energy balance of the environmental LCA (Task 5.2) and the prices of the economic assessment (Task 5.3), where available, are used to calculate the costs required as inputs in the GTAP multiregional input/output model.
  - Conversion of prices:
    Current prices (2021) are provided in € by the economic assessment (Task 5.3). To convert to $ 2011, the reference of the GTAP input/output model, € 2021 is multiplied by 0.8. This factor is based on the mean exchange rate of € and $ in 2011 and the inflation between 2011 and 2020 in the euro zone.
  - Mapping of inputs to country-specific sectors:
    See Table 1. The countries were chosen according to the specified geographical scope (section 3.1.2), i.e. Belgium for the baseline scenario. Deviating from this, countries for inputs that are not available from Belgium such as metals that are not mined there are chosen according to availability on the world market.

- Approach to foreground system:
  The foreground system includes the social risks associated with the work performed in a potential future eForFuel plant. Data on social performance in such plants could not be collected because e-fuel plants do not exist yet at relevant scale. For this purpose, the chemicals sector was taken as a proxy for risks associated with an e-fuel plant. Only risks directly related to work in the chemicals sector were taken into account, not indirect risks resulting from purchases from other sectors.

Table 1: Mapping of inputs to sectors. Unless otherwise specified, the country of the plant location was used to select a country-specific sector.

Item	Sector
CO_2 capture	
Electricity	Electricity
Heat	Electricity
Electroreactor	
Electricity	Electricity
K2SO4 (catholyte)	Mineral products nec, Chemical, rubber, plastic products
Ir for anode	Metals nec (countries according to availability)
Sn for Cathode	Metals nec (countries according to availability)
Electricity for liquefaction of O_2	Electricity
Bioreactor	
Heat	Electricity
Electricity	Electricity
Yeast Extract	Food products nec
Fermentation media - mineral	Mineral products nec
Fermentation media & auxiliaries - chemical	Chemical, rubber, plastic products
Fuel finishing & hydrogenation	
Electricity	Electricity
Road transport	Transport nec
Foreground System	
Personnel costs	Direct risks from chemical, rubber, plastic products
REFERENCE SYSTEM	
Credit: O_2	Chemical, rubber, plastic products
Credit: CH_4 from cells	Electricity
Fossil fuel	Petroleum, coal products
Electricity saved by heat recovery	Electricity
Ethanol 1st generation	Beverages & Tobacco
Ethanol 2nd generation	Wood products
FT jet fuel	Wood products

4. Analysed systems

The systems that were decided upon in the course of the project are presented in the following. They provide the basis for the life cycle assessments. The three main routes are shown in section 4.1. Afterwards, the most important process blocks are presented individually and in more detail (sections 4.2 – 4.5), before reference scenarios are described in section 4.6. Finally, section 4.7 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 3 and Figure 4 for isooctane / isododecane (jet fuel) and propane, respectively. These are the three main routes investigated in eForFuel.

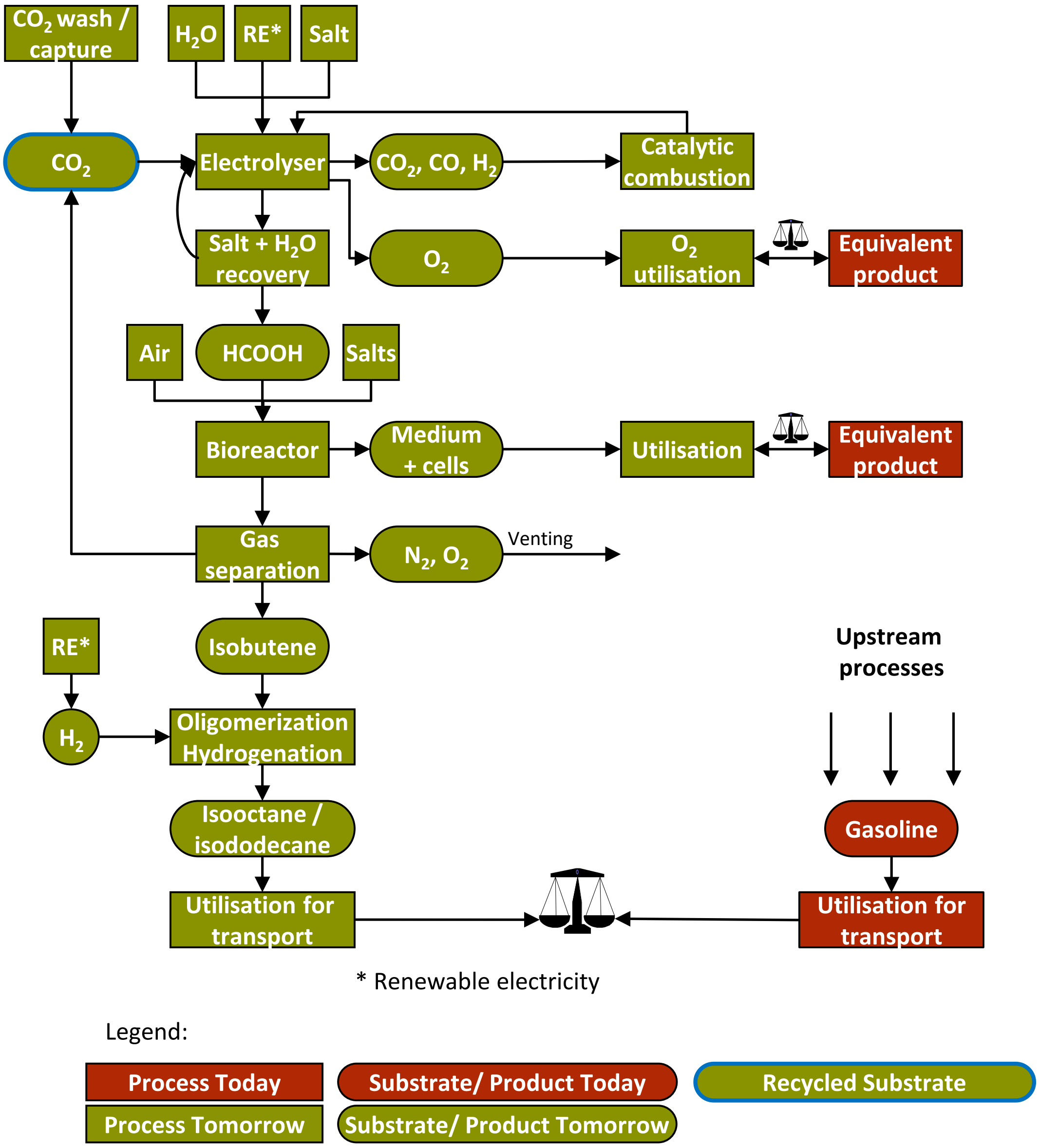

Figure 3: Simplified scheme of the isooctane route

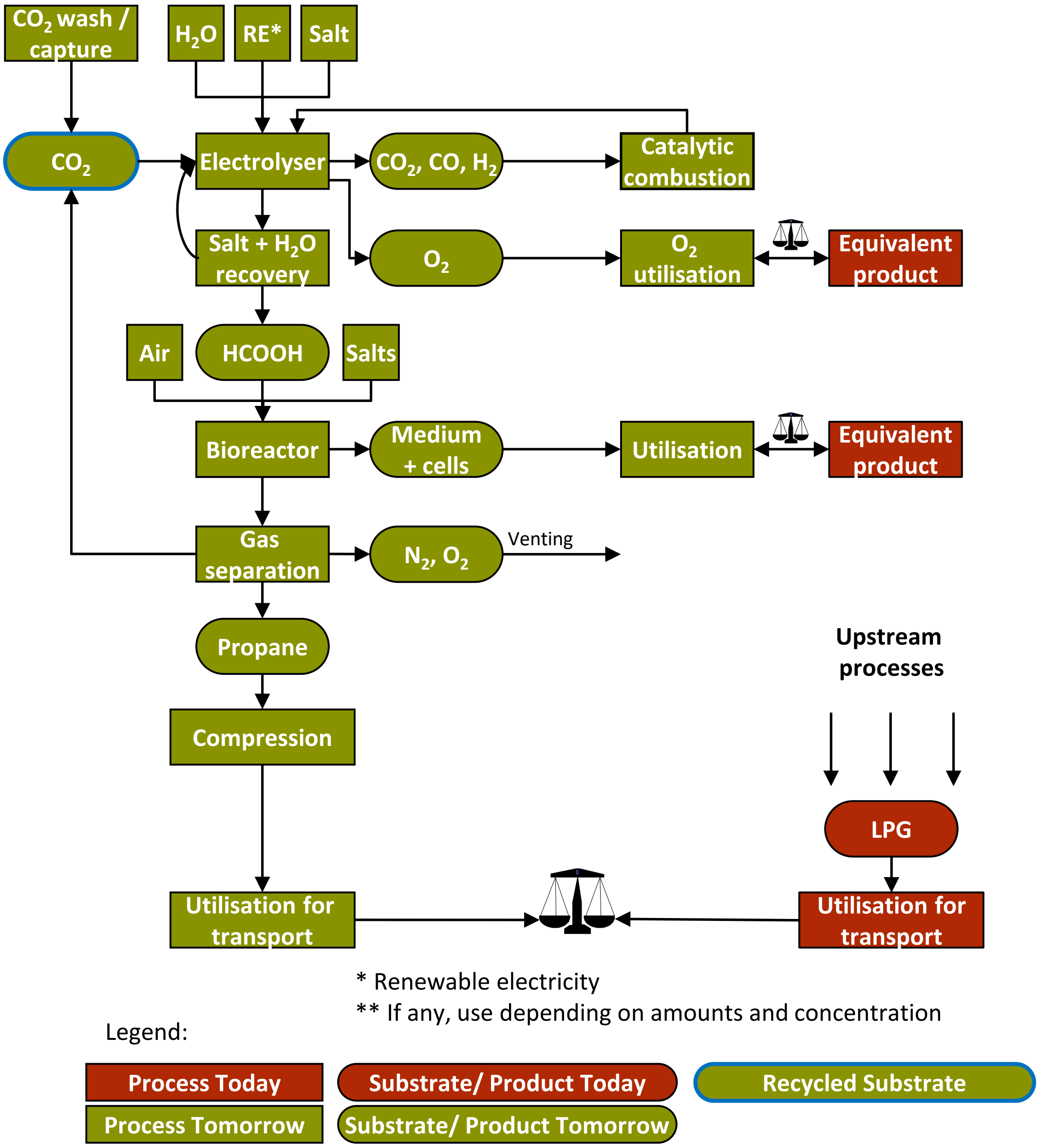

Figure 4: Simplified scheme of the propane route

4.2. Electrochemical production of formic acid (electroreactor)

The electrochemical production of formic acid (Figure 5) 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. 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.

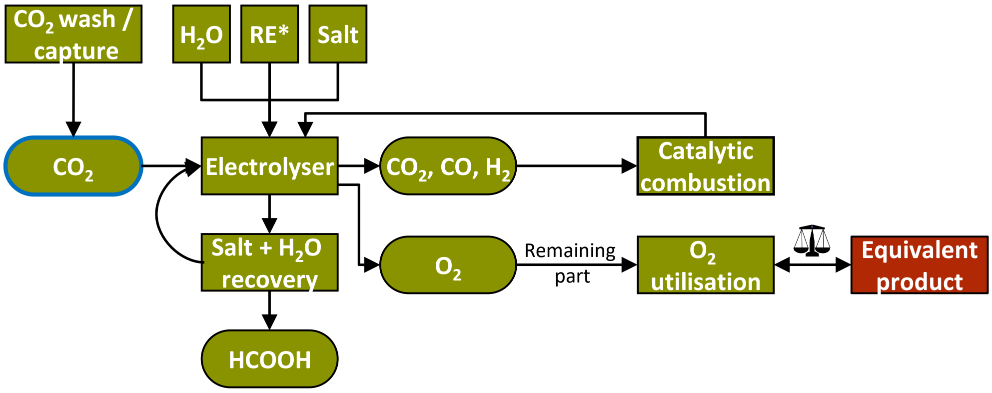

Figure 5: Electrochemical production of formic acid

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 6). 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).

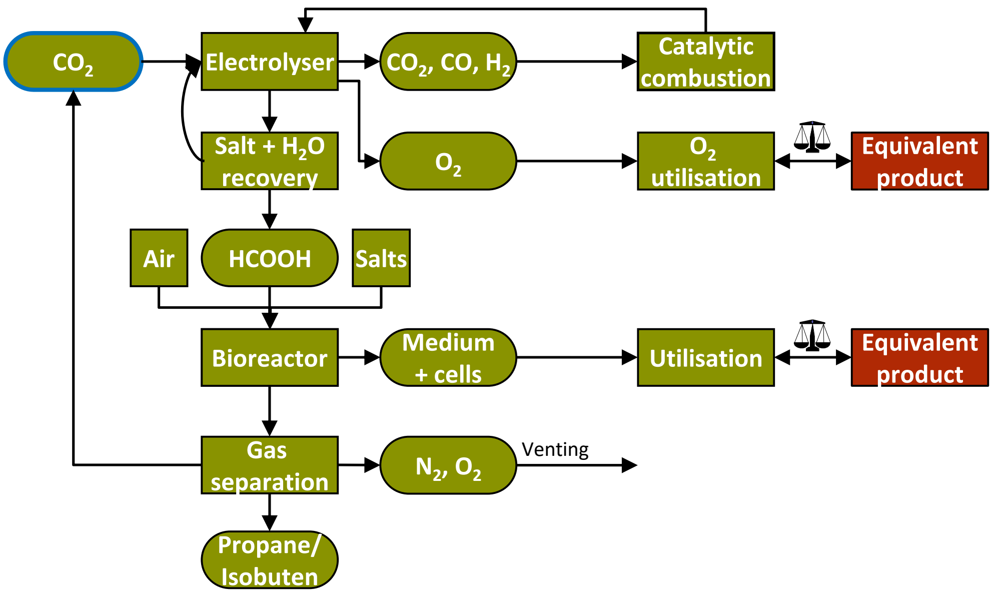

Figure 6: Metabolic conversion of formic acid into hydrocarbons

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 7).

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

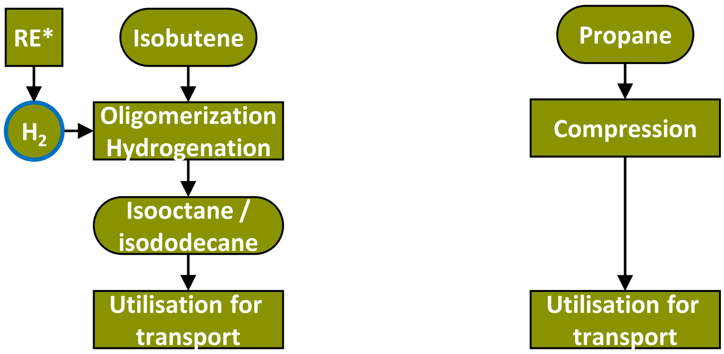

Figure 7: Conversion of gaseous intermediate products (isobutene and propane) into hydrocarbon fuels

4.5. Sources of main inputs

From preliminary calculations performed during the proposal writing phase, it became clear that the results of the sustainability assessment will be crucially influenced by the exact nature / source of three main inputs: electricity, heat, CO_2 and hydrogen.

Electricity source

The main source of electricity will be **renewable electricity** from either wind or photovoltaics (PV).

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).

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.

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.

Hydrogen source

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

4.6. Reference scenarios

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

Reference products

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

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

4.7. Overview of scenarios

Table 2 lists the scenarios investigated on this study. The alternative scenarios were limited to a comparison with electric cars.

Table 2: List of analysed scenarios. 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

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

5. Impacts of eForFuel on society

A social life cycle assessment (sLCA) 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 4.7) is given in section 5.1. Second, the effects of different value chain designs are discussed in section 5.2. Third, the influence of the reference system is analysed in section 5.3. Forth, the influence of location and procurement is presented in section 5.4. Fifth, further negative and positive social impacts not covered by the sLCA including job generation are addressed in section 5.5.

5.1. Overview over social risks: baseline scenario

Social risks associated with different production stages of the electro-microbial fuel production are assessed for all social risks provided by the SHDB aggregated in 25 subcategories (compare section 3.2). These risks are contrasted with the avoided risks in order to put them into context. Figure 8 shows the risks displayed in work-hours needed for the production of 1 MJ transport fuel that are equivalent to work-hours at medium risk.

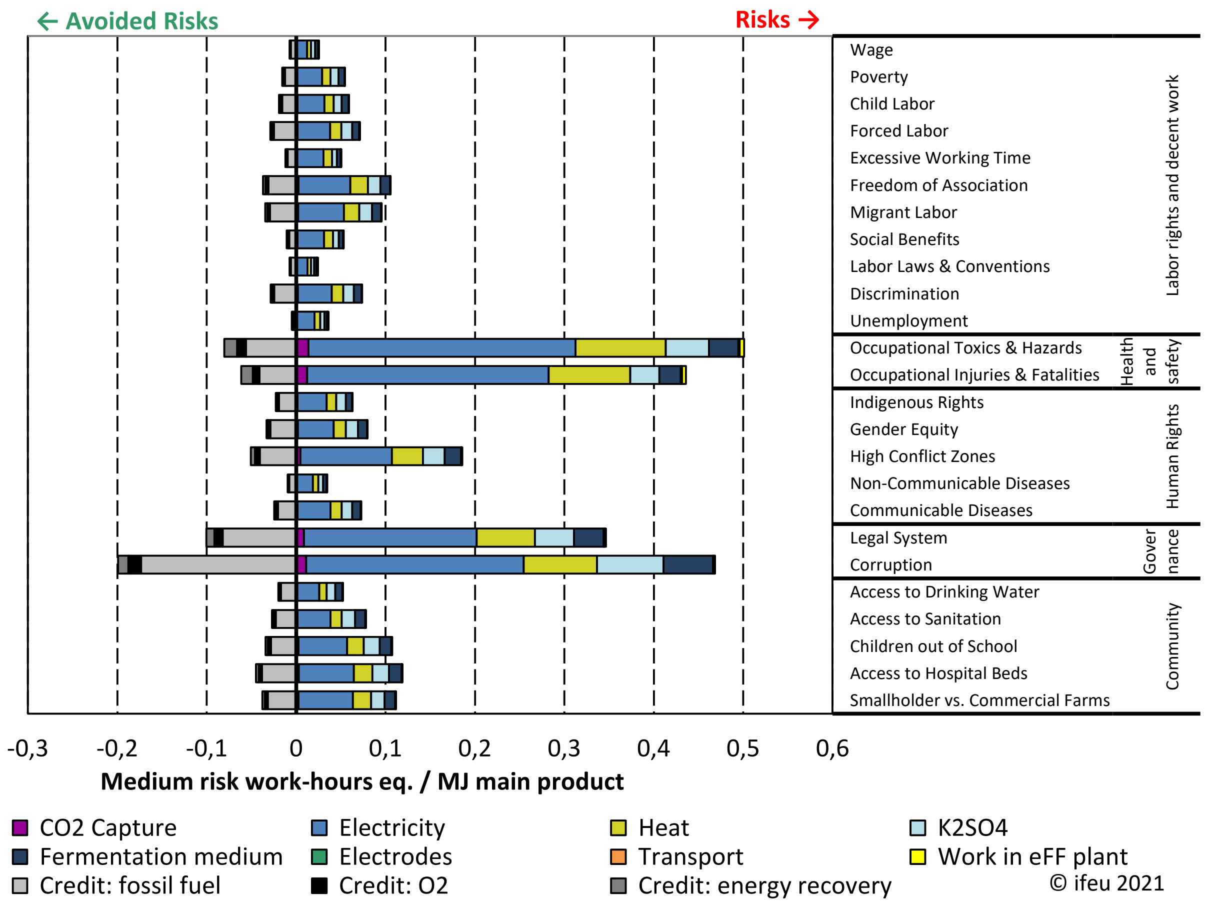

Figure 8: Overview of social risks and avoided risks at subcategory level of electro-microbial e-fuel in the baseline scenario. Transport fuel type: isooctane; technology development: typical; CO_2 source: blast furnace gas from steel plant; country: Belgium.

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

Figure 8 shows that the category "Health and safety" comprising the subcategories "Occupational toxics & hazards" and "Occupational injuries & fatalities" as well as the category "Governance" comprising the subcategories " Legal system" and "Corruption" dominate the social risks. Slightly less social risk but still pronouncedly more than for other subcategories is expected for the subcategory "High conflict zones". Having a look at the process stage level, electricity and heat contribute most to all social subcategories. Electricity and heat are followed by the electrolyte K_2SO_4 of which a large amount is needed due to its low recovery rate and the low overall efficiency of the process. Furthermore, the fermentation media contributes significantly to the social risks. In contrast, the contribution of the electrodes, although containing potentially problematic metals (iridium, tin) typically procured from countries with high social risks, is negligible. This is due to the small amount used in the scenario considered. Similarly, risks from transport and the work in the eForFuel plant are low. Although the analysed location of the plant and of its direct (tier 1) suppliers is Belgium, more than 80% of the work hours at risk are done at higher tier suppliers outside of Belgium and mostly outside of the EU.

Key findings:

- Largest social risks are expected to be connected to the consumption of electricity (including power-based heat). Ongoing major transitions in the sector are expected to cause different but not necessarily substantially lower risks. Further relevant risks arise from K2SO4 and fermentation medium demand.
- Work in the plant itself is only connected to low risks.
- Although the analysed location of the plant and of its direct (tier 1) suppliers is Belgium, more than 80% of the work hours at risk are done at higher tier suppliers outside of Belgium and mostly outside of the EU.
- This scenario of e-fuel production is connected to higher social risks than competing fossil fuels.
- Most relevant social risks originate from Occupational Toxics & Hazards, Corruption, Injuries & Fatalities, Legal system, High conflict zones

5.2. Influence of value chain design on social risks

The processes developed within the scope of the eForFuel project feature immature technology readiness levels (TRL), mainly TRL 4 and TRL 5. However, the sLCA 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 technological developments, value ranges from 'optimistic' via 'typical' to 'conservative' are used. Figure 9 compares the social risks associated with different production stages of the electro-microbial isooctane production to its fossil alternative. The social risks are shown aggregated to a single score as explained in section 3.2 to identify social hot spots.

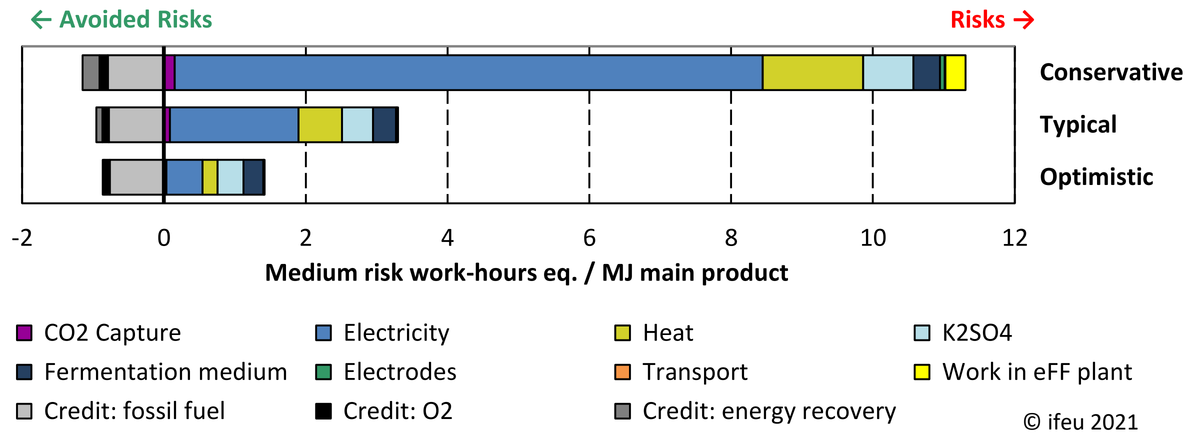

Figure 9: Range of social risks associated with the production of isooctane fuels via electro-microbially produced formate. Results for sub-scenarios under conservative, typical and optimistic boundary conditions are displayed. Transport fuel type: isooctane; CO_2 source: blast furnace gas from steel plant; country: Belgium.

How to read the figure (2nd bar): Under typical boundary conditions, the work in the eForFuel plant and in the supply chain is associated with overall social risks corresponding to about 3 work-hour equivalents at medium risk per MJ of isooctane. About 1 work-hour equivalents at medium risk can be avoided because conventional gasoline and its production is replaced by isooctane. These overall social risks correspond to the sum of all individual social risks displayed by sub-categories in Figure 8. The other bars represent the same scenario modelled under more or less favourable boundary conditions including different efficiencies reached in further technology development.

Figure 9 reveals that only the risks associated with an 'optimistic' scenario are in the order of magnitude of the alternative fossil fuel. In this case, the social risks of electricity and heat is significantly lower than in the 'typical' case, while the contribution of other process stages remains similar. With 'conservative' values, electricity and heat largely dominate the strongly increased overall social risks.

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. Figure 10 compares the social risks associated with different production stages of the electro-microbial fuel production to their fossil alternatives. The social risks and avoided social risks of producing different fuel types do not differ significantly considering the underlying uncertainties.

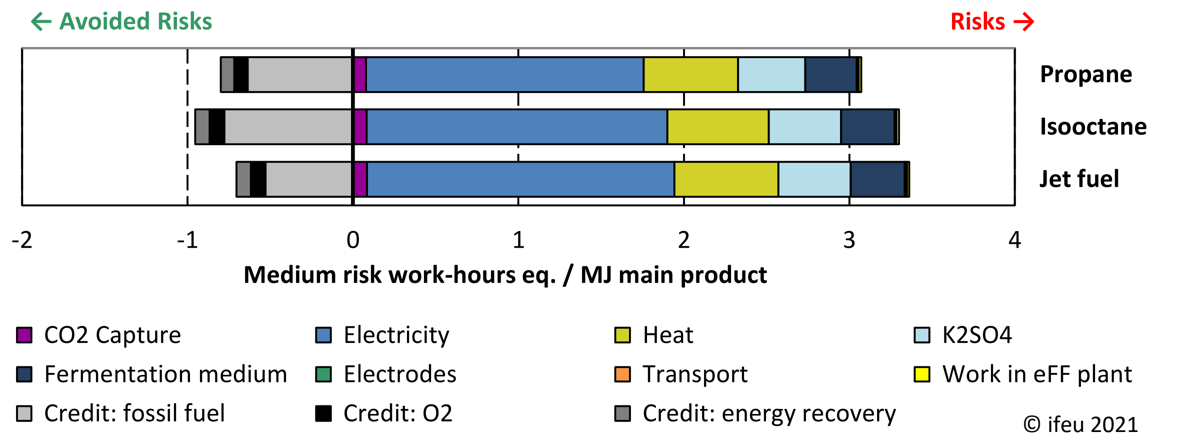

Figure 10: Social risks associated with the production of various transport fuels via electro-microbially produced formate. Technology level: typical; CO_2 source: blast furnace gas from steel plant; country: Belgium.

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 capture methods. To cover the full range of possible scenarios, the sources and capture methods with the lowest and the highest resource demands are considered. As an almost pure CO_2 off-gas stream can be obtained from an bioethanol plant, the least resources are required for capturing CO_2

from this source. Direct air capture (DAC) needs a comparably high energy input. High-temperature absorption DAC is considered as a proxy for other DAC technologies.

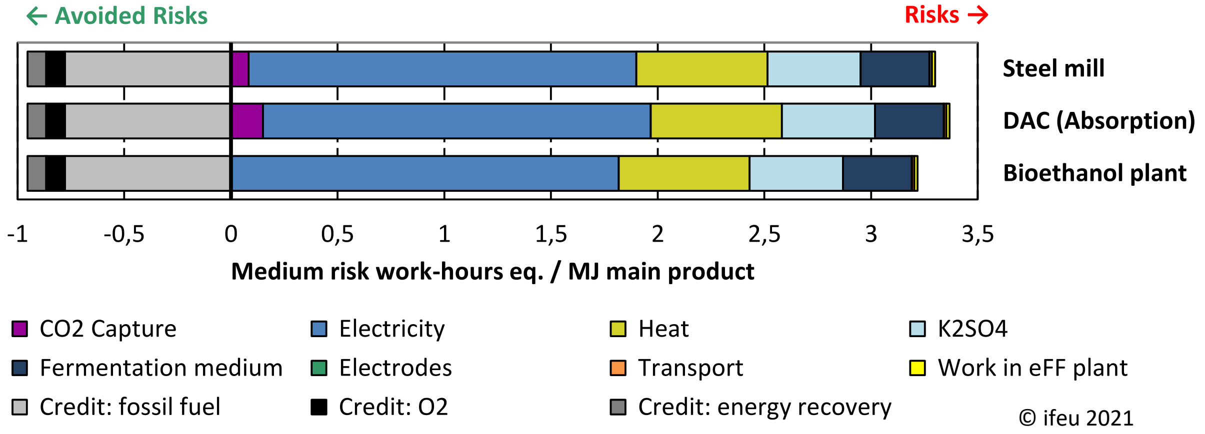

Figure 11: Social risks associated with the production of isooctane via electro-microbially produced formate for different CO_2 sources. Transport fuel type: isooctane; technology development: typical; country: Belgium.

The social risks associated with CO_2 capture increase as the demand for inputs increases. The social risks are dominated by the energy demand of the capturing process. Further inputs, such as MEA in case of amine wash as considered for the steel mill and the bioethanol plant, are negligible. Compared to other process steps, the potential impact of CO_2 capture is low.

Key findings:

- Possible efficiency improvements by further technology development have a crucial influence on social risks: The less energy and materials are required, the lower are the risks in the supply chain.
- Risks related to electricity/heat provision do not clearly dominate over other risks any more if efficiencies as set for the optimistic sub-scenario are reached.
- Overall risks for e-fuel are in the same order of magnitude as for fossil fuels as long as at least efficiencies as set for the typical sub-scenario are reached.
- The choice of the downstream processing route and associated fuel product (propane, isooctane, isododecane) has no substantial influence on social risks.
- Most risks related to CO_2 as feedstock are caused by electricity consumption for its capture, which is in all cases small compared to other electricity consumption. These risks are small in case of CO_2 capture from flue gases (steel mill, fermentation), slightly larger for direct air capture and negligible for CO_2 from bioethanol plants.

5.3. Influence of the choice of reference system

Isooctane and jet fuel may also replace other renewable alternative fuels such as biogenic ethanol or Fischer-Tropsch jet fuel (FT jet fuel). Figure 12 shows a comparison of the social risk associated with electro-microbially produced fuels and renewable alternatives. Compared to the replaced fossil fuels, the social risks associated with replaced biogenic ethanol or Fischer-Tropsch jet fuel are significantly higher following the standard evaluation methodology based on the social hotspot database but nevertheless in the same order of magnitude (see section 3.2 for details). This mainly results from higher prices of biofuels and a higher labour intensity of their production in combination with similar to lower specific risks per work-hour in the biofuel supply chain. This confirms intuitive expectations for food and feed crop-based (first generation) biofuels for which biomass is known to be produced partially under poor working conditions in particular in the Global South. Second generation biofuels, however, are supposed to be produced primarily from residues arising in Europe, which could reduce the risks in the supply chain. The multi-regional input/output database underlying the social hotspot database is however not fine-grained enough to differentiate specific supply chains. It allocates all risks from imports e.g. of the forestry sector of a country evenly to all products from this sector no matter if a specific product is explicitly produced only from domestic residues. The same holds true for social issues such as food security and land tenure that are known to be a problem associated with imported biomass used for (food and feed) crop-based biofuels (e.g. [German et al. 2011]): These issues are directly or indirectly covered by the social hotspot database but specific attribution is even more challenging because both food security and land tenure are indirectly affected by *expanding* agriculture via *increasing* land use, not directly through work in existing agriculture itself.

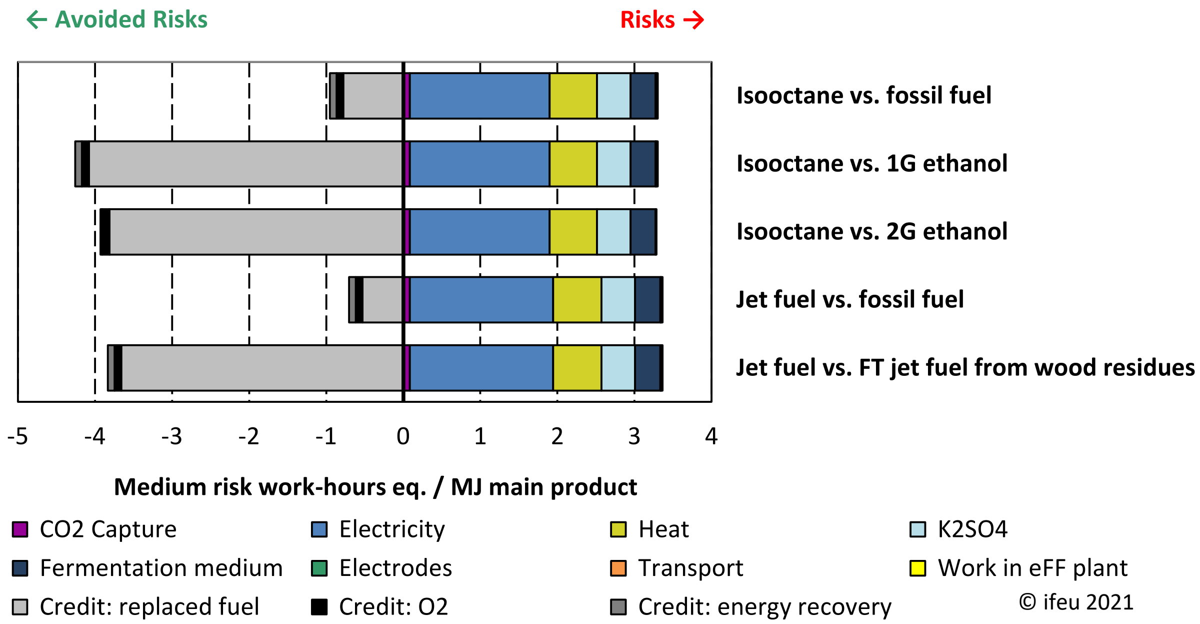

Figure 12: Social risks associated with the production of various transport fuels via electro-microbially produced formate and their alternatives. Technology level: typical; CO_2 source: blast furnace gas from steel plant; country: Belgium. Abbreviations: 1G ethanol: 1st generation ethanol (from edible biomass), 2G ethanol: 2nd generation ethanol (from non-food biomass), FT jet fuel: Fischer-Tropsch jet fuel.

Social risks of fossil fuels and biofuels have been compared in detail using the social hotspot database, too, and taking into account individual aspects of the value chains in detail by [Ekener-Petersen et al. 2014]. That study came to the conclusion that both fossil and biofuels display high or very high risks of negative social impacts that depend more on the country of origin than on the kind of fuel. Furthermore, as in agreement with our analysis, they concluded that identified risks can serve as a basis for a mitigation strategy but that a careful interpretation is necessary to avoid unfair comparisons.

Taken together, this comparison to various biofuels as alternative reference system can substantiate the insight from comparing to fossil fuels that risks of the analysed electro-microbial fuels are in the same order of magnitude if at least the efficiencies postulated in the sub-scenarios under typical conditions are reached. The replacement of (food and feed) crop-based biofuels in particular could in tendency help to reduce social risks in fuel supply chains although this requires more detailed studies. If these efficiencies cannot be reached, an optimisation of the production system seems more promising to reduce social risks than the mitigation of risks in the supply chain.

Key findings:

- Risks of the analysed electro-microbial fuels are in the same order of magnitude as for competing fuels including biofuels if at least the efficiencies postulated in the sub-scenarios under typical conditions are reached.
- Otherwise, an optimisation of the production system seems most promising to reduce social risks.
- If (food and feed) crop-based biofuels are replaced, this could in tendency lead to the greatest mitigation of social risks in fuel supply chains but the underlying data has to be scrutinised to substantiate this finding.

5.4. Influence of location and procurement on social risks

To assess the impact of the plant location in Europe, Belgium, Denmark and Spain were exemplarily selected (see section 3.1.2). Figure 13 shows a comparison of the social risk associated with electro-microbially produced fuels and renewable alternatives. Inputs are set to be purchased in the respective countries and reference products from the same country are set to be replaced in the assessed scenarios.

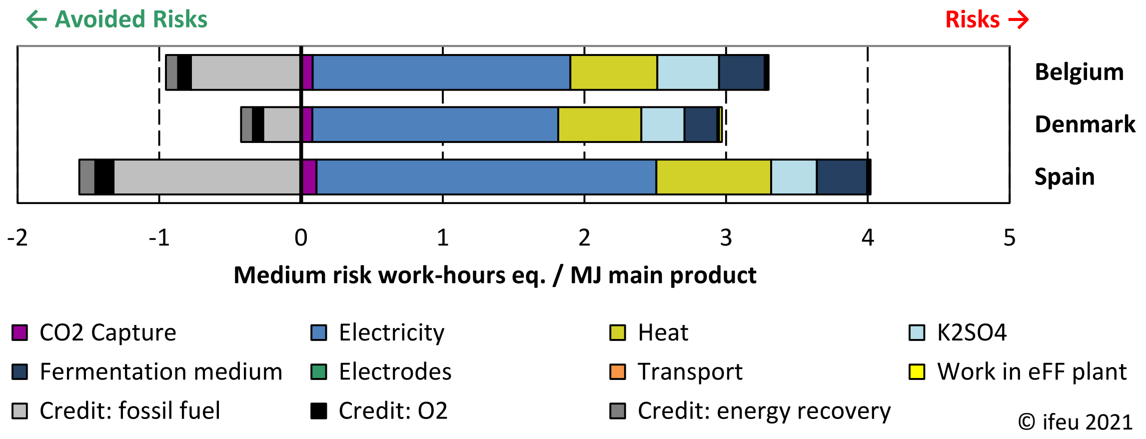

Figure 13: Social risks associated with the production of isooctane via electro-microbially produced formate for different production countries. Transport fuel type: isooctane; technology development: typical; CO_2 source: blast furnace gas from steel plant.

The extent of social risks and hotspots are very similar across the European countries studied, with risks tending to be lower in the northern EU countries. Deviations mainly results from different average supply chains in these countries. In all cases, most social risks are associated with the electricity and heat demand of the eForFuel process. Therefore, the social risks connected to electricity purchases from different European and North African countries were compared in Figure 14. North Africa was included because it is currently discussed for imports of renewable electricity to Europe.

Figure 14 shows that there are more social risks associated with electricity from North African countries than with electricity from European countries. While the social risks in the electricity sector in North Africa is mainly due to social risks within this region, the social risks associated with electricity from Europe results from imports from other countries. Electricity from Norway is also connected to particularly low risks, among other reasons, because the hydropower, which dominates there, neither requires problematic fossil energy carriers nor many other problematic resources such as rare earths or cobalt. The data cannot be used for a quantitative comparison because electricity price levels are very different in the analysed countries. In contrast, qualitative differences discussed above are largely independent of this quantitative distortion. Although the analysis is based on supply chain data from 2011, when most electricity is based on fossil fuels, the trends described are also expected to apply to renewable energy in 2030. Specific social risks connected to renewable electricity generation cannot be deduced from the most recent version of social indicators because they are still outweighed by existing social impacts from fossil energy conversion in the sector in most countries. This is addressed by a literature analysis in section 5.5.

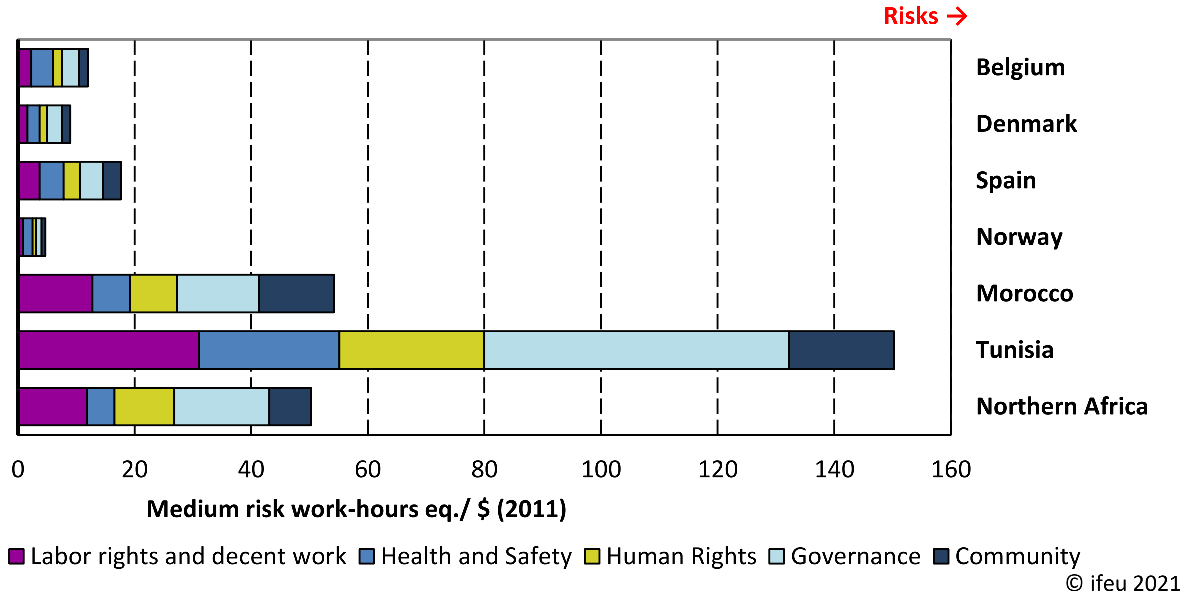

Figure 14: Social risks associated with the purchase of 1 $ electricity at 2011 prices in different countries.

How to read the figure: The sections of the 1st bar correspond to the social risks associated with electricity worth of 1 $ at 2011 price levels purchased in Belgium, differentiated by the different social impact categories. For the other bars, the country was varied.

In the baseline scenario (see Figure 8), the use of iridium (Ir) and tin (Sn) for the electrodes does not substantially contribute to social risks although mining is often associated to substantial social risks. For the baseline scenario, the main mining countries (Ir: South Africa, Sn: China) were set. However, the social risks in other mining countries may exceed these risks, leading to non-negligible contributions. Thus, Figure 15 compares the social risks associated with the purchase of these metals from different countries with substantial world market shares for these metals.

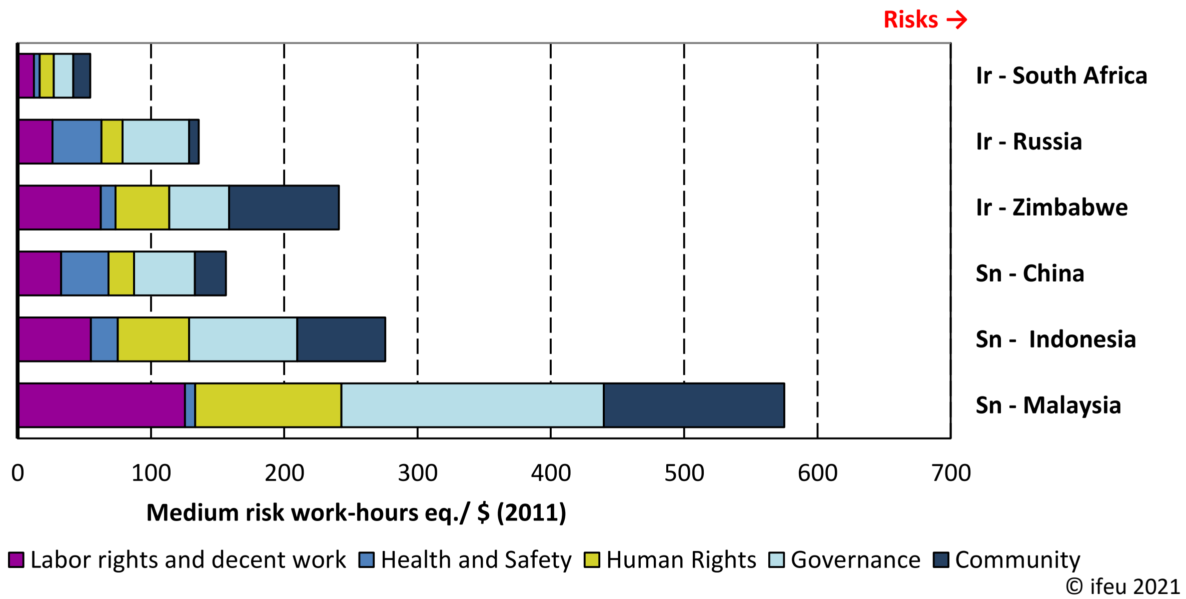

Figure 15: Social risks associated with the purchase of 1 $ iridium (Ir) or tin (Sn) at 2011 prices in different countries.

The highest social risks are associated with mining Ir in Zimbabwe and Sn in Malaysia. To assess their contribution to the overall social risks associated with the production of electro-microbial fuels, Figure 16 compares the baseline scenario (Ir: South Africa, Sn: China) with a scenario where Ir is mined in Zimbabwe and Sn in Malaysia. Despite the high social risks per $, this input has no influence on the overall balance due to the small quantity used.

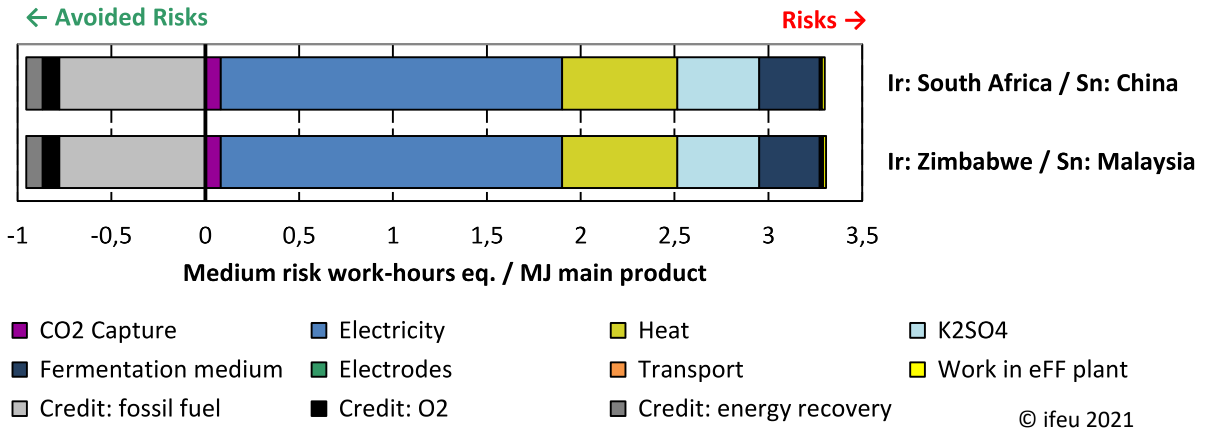

Figure 16: Social risks associated with the production of isooctane via electro-microbially produced formate for different origins of the metals used for the electrodes. Transport fuel type: isooctane; technology development: typical; CO_2 source: blast furnace gas from steel plant, country: Belgium.

Key findings:

- The country of origin is crucial for the social risks involved in purchasing goods. Although different price levels make quantitative comparisons difficult, qualitative differences can be derived.
- The magnitude of social risks and the hotspots are very similar for electricity and e-fuel production in analysed European countries with lower risks in tendency in northern EU countries. This is mainly determined by differences in average supply chains e.g. for crude oil in these countries.
- Electricity imports from North Africa are associated with higher social risks than electricity production in the EU. While domestic social risks dominate in Norther African countries, “imported” risks dominate for EU countries.
- Electricity from Norway is a connected to particularly low risks amongst others because water power, which dominates there, neither requires problematic fossil energy carriers nor much other problematic resources such as rare earths or cobalt.
- Even if metals for catalysts stem from countries with problematic mining sectors, risks remain small compared to the remaining supply chain of the analysed e-fuels due to small amounts used.

5.5. Social impacts not covered by sLCA

The main method applied in this study, social life cycle assessment (sLCA), is originally designed to identify hot spots of social risks or negative social impacts in the supply chain of a certain product based on risks identified in similar supply chains in the past. This does not cover some social aspects that can nevertheless be very relevant for a potential future implementation of electro-microbial fuels according to the eForFuel concept.

Additional potential negative impacts

The by far most important social risks for the analysed systems arise from the enormous demand for renewable electricity. Available data from the past, which stem from a largely fossil-based electricity sector, can however only give an indication that risks connected to electricity supply are important (see also section 5.1). The kind of current or even future risks connected specifically to renewable electricity supply cannot be deduced from the most current sLCA databases such as the SHDB. This is expected, because the electricity sector is undergoing a massive transformation that will continue and possibly accelerate in the coming years.

This data gap can at least partially be filled by taking up conclusions from studies using a wide array of other sociological and related methodologies to study social risks associated with large scale renewable electricity supply including imports. Most studies see positive social impacts dominating but point out that there are often certain stakeholders or groups that are negatively affected and persons that have a strong opinions against new installations, which others may consider justified or not [Agterbosch et al. 2007; Hanger et al. 2016; Schmitt 2018; Terrapon-Pfaff et al. 2019]. It is observed that the implementation of very similar technical systems such as wind turbines can cause fierce resistance in one case and wide local support. Important factors for this different perception may include:

- Participation in economic benefits
- Provision of information and participation in decision making processes
- Acceptance and background of proponents of new installations

External investments such as from large companies in local communities or from developed in less developed countries (keyword neo-colonialism) are often viewed particularly critically, potentially because they are associated with a loss of control and autonomy. Such negative effects are larger the larger the installations are. Further potential negative social impacts that were identified [Agterbosch et al. 2007; Hanger et al. 2016; Schmitt 2018; Terrapon-Pfaff et al. 2019]:

- Displacement of former partially extensive users from land used for installations
- Exclusion of less skilled workers and local firms.
- Effects of migration of external workers of large facilities into local communities on culture, political influence, prices of resources such as housing or food (in developing countries).
- Impacts on health, safety and environment including noise emissions and shadows of wind turbines (partially covered by sLCA as far as already implemented).
- Poor labour conditions (mainly covered by sLCA if socio-economic structures resemble those of the existing electricity sector).

A large part of the negative impacts is connected to the transition process, which are mostly not covered by sLCA, while others are connected to regular operations itself. Further risks in the supply chains of building solar panels and wind turbines have to be studied separately, too, because this data is not yet sufficiently covered by sLCA databases. Despite small amounts needed, supply chains of rare earths and metals such as cobalt, which is primarily mined in the Democratic Republic of Congo, are known contain serious social hot spots.

In general, positive examples show that in particular small and medium scale wind and solar power installations can be realised with broad public acceptance and benefits for all stakeholders. However, resources for producing e.g. wind turbines are known to be connected with serious social risks although only small amounts are needed. Therefore, efficiencies should be increased, scales should be limited and the implementation process should pay attention to just and inclusive processes and fair sharing of burdens and benefits.

Potential positive impacts

Among the most important benefits for local communities is the generation of jobs along the value chain. These include from local to global level:

1. Operators of the eForFuel plant itself (direct jobs)
2. Staff involved in maintenance, administration and sales (direct jobs)
3. Staff of external service providers such as cleaning, transportation, waste disposal (indirect jobs)
4. Staff of external suppliers of input materials (indirect jobs)
5. Jobs generated in the general economy by spending additional income and profits (induced jobs)

For a medium size eForFuel installation as considered in the sub-scenario under typical conditions, the following number of jobs was estimated:

Table 3: Job generation of a eForFuel plant with a capacity of 80 000 t e-fuel per year. FTE: full time equivalents

Kind of jobs	Number of FTE	Source/comment
Operators (direct)	20	Provided by Task 5.3 (ArcelorMittal)
Supervision, administration (direct)	15	Own estimate based on ratios in similar installations
Maintenance by own employees (direct)	No data	No data on CAPEX available
External services and suppliers (indirect)	150	Based on ratio from [Godden 2019]
Induced jobs	(0)	Assessed scenarios are not profitable [Peleman & Van der Stricht 2021]

The installations depicted in the sub-scenarios under optimistic, typical and conservative conditions have capacities of about 80 000, 3 000 and 170 t of e-fuels per year, respectively. While the number of operators and supervisors does not scale much, the number of jobs generated at suppliers scales almost linearly with the capacity. Most relevant for estimating social benefits of a potential future implementation of the eForFuel concept is the largest of these scales because this is closest to an industrial scale plant. These figures can however only be taken as a very rough indication of the number of jobs that could be generated and have to be adapted in future studies once an economically viable and probably more efficient configuration is found and data on the plant infrastructure becomes available based on these configurations.

The provision of e-fuels can moreover be an important option to provide transportation services in a defossilised and climate neutral world. A substantial share of these services fulfils socially beneficial needs.

It however will have to be scrutinised which share really contributes to well-being and the rest will have to be reduced as far as possible to limit the strain on resources the provision of e-fuels creates.

Key findings:

- Social risks created by the emerging large-scale renewable electricity production, which is crucial for the assessed e-fuels, cannot be determined by sLCA but further methodologies have been successfully used to study these impacts as reported in the literature.
- Direct impacts are rather determined by the way of implementation and can be overall very positive if just and inclusive processes are followed and burdens and benefits are shared in a fair way.
- Indirect risks in the supply chain of providing resources such as cobalt for wind turbines can be critical and have to be managed.
- Plants producing e-fuels according to the eForFuel concept can provide a certain number of jobs in the plant itself and many more in the supplying industries.
- E-fuels can provide for valuable transportation services that contribute to well-being. Other transportation needs to be reduced as far as possible.

6. Social and policy barriers to implementation

After assessing the potential impacts of a future implementation of the eForFuel concept on society in the previous section (5), this section will now take the opposite perspective and explore potential impacts of society on a future implementation of the eForFuel concept, i.e. social and policy barriers to implementation. This includes public perception, market acceptance as well as the regulatory framework and policies.

6.1. Public perception

In the eForFuel project, a public perception survey has been conducted, which examined how recycling of industrial CO_2 emissions into drop-in fuels (so-called recycled carbon fuels, RCF[1]) would be perceived by European citizens. The survey was performed in the form of 6 citizen engagement activities across Europe (Portugal, Denmark, the Netherlands, Estonia, Spain & Italy) involving 165 participants. The events were divided into three sections: (i) fossil fuels, CO_2 and carbon capture, (ii) project ambitions and possible applications and (iii) economic dimensions, subsidies and energy sources. The survey design included multiple- and single-choice questions as well as qualitative reflection questions. For more details, please refer to [Schmidt & Youssef 2020a].

The results for section 1 reported by [Schmidt & Youssef 2020a] indicate that most participants were very well acquainted with the topics greenhouse effect, global warming and climate change. An overwhelming majority indicated that they considered the reduction of CO_2 emissions from fossil fuels important. Overall, carbon capture and utilisation (CCU) for fuel production was viewed positively, however, some participants expressed concerns that CCU treated the symptoms rather than cured the cause of the problem (increase of atmospheric CO_2 concentrations). Therefore, CCU was seen as one of many measures, perhaps during a transition period.

In section 2, participants learned more about eForFuel concept and evaluated different fuel types, potential target products of the eForFuel concept and the use of GMO. Regarding potential target products of the eForFuel concept, [Schmidt & Youssef 2020a] found a cautiously positive view on most product categories (except for animal feed, which was viewed rather negatively), with a slight preference for aviation fuel. Around two thirds of the participants had a neutral to positive opinion regarding the use of GMO, but with comments towards biosafety and biosecurity. Figure 17 shows that recycled carbon fuels (RCF[1]) were rated more favourable than fossil fuels but less favourable than fuels from renewable sources (so-called renewable fuels of non-biological origin, RFNBO[2]).

[1] liquid and gaseous fuels that are produced from […] waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations (as defined in the RED II, Article 2(35))

[2] liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass (as defined in the RED II, Article 2(36))

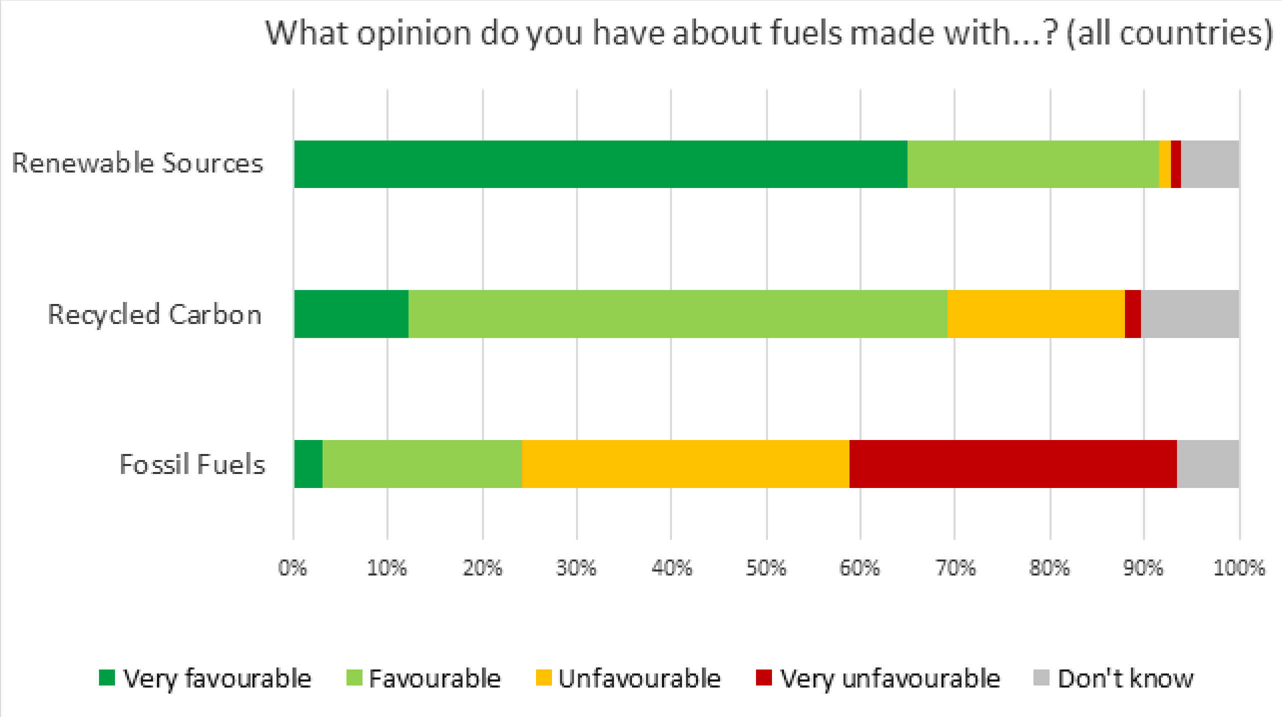

Figure 17: Evaluation of the production of fuels from renewable sources (RFNBO), recycled carbon (RCF) and fossil fuels across all six countries [Schmidt & Youssef 2020a]

In section 3, participants were asked to evaluate financial measures and electricity sources. Most participants evaluated subsidies positively, though many noted that they would also like to remove subsidies for fossil fuels. Regarding electricity sources, most respondents preferred dedicated renewable electricity sources, as long as companies could afford them (Figure 18).

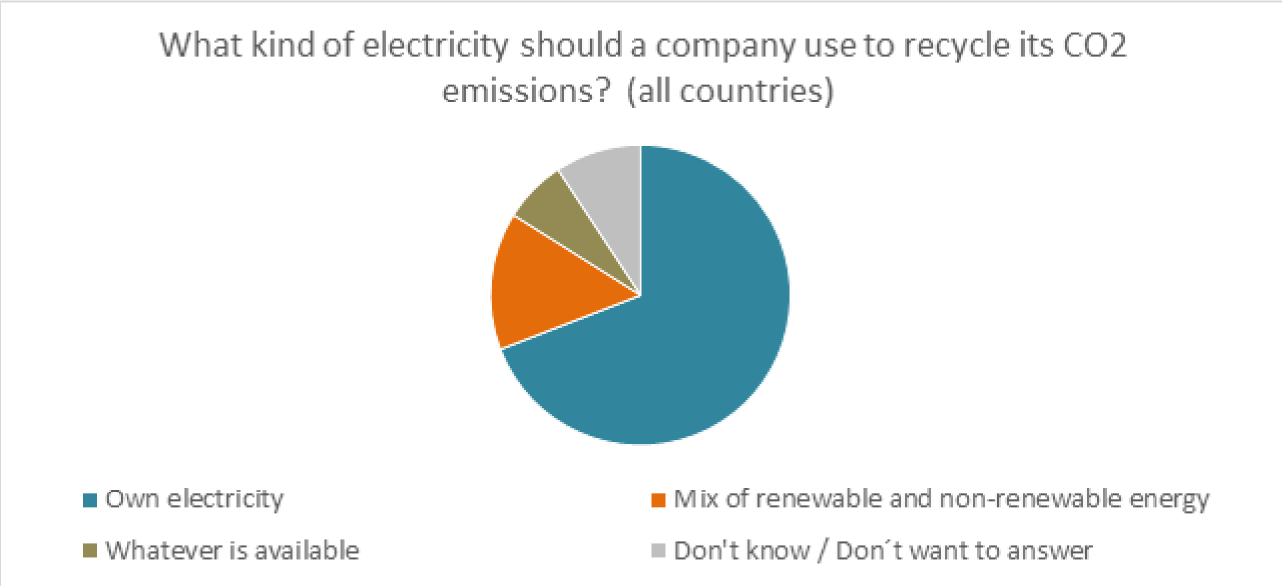

Figure 18: Electricity sources favoured for CO_2 recycling across all six countries [Schmidt & Youssef 2020a]

[Schmidt & Youssef 2020a] conclude that most participating citizens were favourably inclined to the eForFuel concept and the recycling of industrial CO_2 emissions into drop-in fuels. However, there were some reservations about using this CO_2 source which was considered a treatment of symptoms rather than curing the cause of the problem (increase of atmospheric CO_2 concentrations), e.g. by a systemic change. Nevertheless, since the topic is of high relevance to citizens, the majority was in favour of the technology, but it was seen as one of many possible measures rather than as the silver bullet. As opposed to fuels from recycled carbon (RCF), fuels from renewable sources (RFNBO) were seen much more favourable. This is important to keep in mind since the eForFuel concept is not necessarily bound to the use of CO_2 of non-renewable origin (i.e. recycled carbon from fossil point sources). Indeed, the eForFuel concept could also use biogenic or atmospheric CO_2 (both of which are neutral in terms of atmospheric CO_2 concentrations). In this case, the obtained fuels would qualify as RFNBO which were very favourably viewed.

It is important to note that [Schmidt & Youssef 2020a] underline that many participants of the public perception survey found it difficult to debate and to form an opinion without having any numbers (not even approximations) in terms of CO_2 emission savings, costs or benefits to society at hand. This can be explained by the fact that at the time the survey was conducted, the desired numbers were not yet available since the integrated sustainability assessment was still in progress. Conversely, this means that the results of the public perception survey represent a snapshot from the first half of the project duration and are possibly subject to change if the survey were repeated. [Offermann-van Heek et al. 2020] for example showed that information on environmental impact and energy demand can change public preferences.

Furthermore, this public perception survey involving 165 participants did not catch a representative sample of the European population. Admittedly, this was not the aim of the public engagement activities, but must be taken into account when interpreting the results. In recent years, a wealth of papers on the topic has been published on specific CCU products [Arning et al. 2018; Simons et al. 2021], on technology comparisons [Linzenich et al. 2021] and on country-specific views [Jones et al. 2017; Perdan et al. 2017]. It has been pointed out that due to the low public knowledge about CO_2-based technologies, CCU and CCS are often confused, as observed in a stakeholder dialogue series. This entails the risk that assumptions derived from CCS projects, which have attracted considerable opposition in the past in some regions, might be transferred to CCU and affect its perceptions and acceptance [Arning et al. 2019; Bruhn et al. 2016].

Last but not least, despite best efforts regarding the provision of objective and transparent information on the eForFuel concept, it is clear that it is just one CCU concept among many others. It is unlikely that citizens are willing to engage in a 3 hour event on each CCU concept to form an opinion. Thus, public perception will hardly differentiate between various concepts and generalisations will be the consequence – maybe unless a specific concept has a very unique feature. For eForFuel, this means that public perception will to a large extent be influenced by general views on CCU which are also present in the media. In the latter, the spectrum of representatives currently ranges from very critical individuals to ‘CCU believers’ and it is impossible to predict which side will win the fight for interpretative sovereignty. It is therefore of utmost importance to carefully think about a communication strategy, as also highlighted by [Arning et al. 2021].

To summarise: on this basis, no final conclusions can be drawn whether public perception is a potential barrier to the implementation of the eForFuel concept. Currently, this does not seem to be the case but future developments are unpredictable.

6.2. Market acceptance

In the eForFuel project, a preliminary business plan has been compiled by [Candotti et al. 2021]. As part of that report, a preliminary market exploration of eForFuel target markets has been conducted, including the markets of CO_2, formic acid, e-fuels as well as (bio-)isooctane/isododecane and (bio-)propane. Market sizes and market prices for the main CO_2-based compounds were studied and classified as (i) high value-added products having a low market volume and (ii) low value-added products having a large market volume.

In terms of market size, it became clear that the current fuel market can absorb (almost) any quantity of e-fuels. The bottleneck is rather the required huge amounts renewable energy (RE) and the area for RE installations - at least in Europe. However, since fuels are generally considered low value-added, large volume products, the eForFuel products may have difficulties to compete on the market. Therefore, it might be worthwhile to focus on high value-added, low volume products. This could also entail higher environmental benefits, as pointed out by [Rettenmaier et al. 2021], and thus represent a win-win situation.

The preliminary market exploration comes to the conclusion that:

- One of the market opportunities that could be opened by eForFuel is the development of an efficient system for the electrochemical reduction of CO_2 to formic acid that will serve to establish efficient strategies for chemical energy storage
- Product positioning of formic acid in comparison to other compounds is difficult to assess due to the high uncertainty that characterize low TRL technologies
- There is a need for further R&D to bring the TRL of electrochemical reduction to higher levels.

In addition to the preliminary market exploration, [Candotti et al. 2021] also applied a patent-based methodology for quantitative forecast of the serviceable obtainable market to the entire eForFuel project. For more details, the reader is referred to that report.

Market acceptance also has a technical perspective. Two out of the three main fuel products targeted in eForFuel, namely isooctane and propane, can be considered drop-in fuels that fit with the current fuel and vehicle infrastructure. However, the future of internal combustion engines vehicles in road transport is rather unclear and [Candotti et al. 2021] conclude that *"Electrification will undoubtedly be the main driver of decarbonisation for light-duty vehicles and possibly for heavy-duty vehicles in short distances."*

The eForFuel project's third main fuel product, isododecane, would target air transport/aviation which is considered very promising by [Candotti et al. 2021]: *"However, maritime and aviation transport will be hardly electrified and decarbonisation will be pursued under other forms such as biofuels and e-fuels. While the first are seen as the main solution in the short term, in the long term e-fuels will open a new window of opportunities for players in a highly regulated market."* However, it must first be verified that isododecane is acceptable under the applicable fuel standards and if so, up to which percentage it could be blended into conventional jet fuel.

In summary, e-fuels generally have a chance of a positive market acceptance. On the one hand, the fuel market is huge, but on the other hand, fuels are considered low added-value, high volume products. At the end of the day, the costs of the electro-microbial fuels will determine their market acceptance. Moreover, the transport sector will have to undergo a massive transformation and therefore, those subsectors in which greenhouse gas emissions are hard to abate (e.g. aviation) should be targeted primarily.

6.3. Regulatory framework and policies

In the eForFuel project, the importance of policies and regulations for setting the framework of current and future research and development activities has been clearly and repeatedly highlighted during two rounds of interviews with a total of 14 expert stakeholders [Schmidt & Youssef 2020b; Pei et al. 2021]. Moreover, the regulatory framework and policies have been studied by [Parco & Rettenmaier 2020].

In terms of the regulatory framework, Directive (EU) 2018/2001, the so-called Renewable Energy Directive or RED II, has been identified as most important, since it specifies the conditions under which certain types of renewable fuels are eligible to count towards the renewable energy targets set therein [European Parliament & Council of the European Union 2018]. Notably, a number of open issues related to Articles 25, 27 and 28 of the RED II might affect the short- and medium-term market deployment of eForFuel products. The consequences of this absence of legislation are explained in the following.

Article 25: Mainstreaming renewable energy in the transport sector

> 1. In order to mainstream the use of renewable energy in the transport sector, each Member State shall set an obligation on fuel suppliers to ensure that the share of renewable energy within the final consumption of energy in the transport sector is at least 14 % by 2030 (minimum share) in accordance with an indicative trajectory set by the Member State and calculated in accordance with the methodology set out in this Article and in Articles 26 and 27.
>
> […]
>
> For the calculation of the minimum share referred to in the first subparagraph, Member States:
> (a) **shall** take into account renewable liquid and gaseous transport fuels of non-biological origin also when they are used as intermediate products for the production of conventional fuels; and
> (b) **may** take into account recycled carbon fuels.
>
> […]
>
> 2. The greenhouse gas emissions savings from the use of renewable liquid and gaseous transport fuels of non-biological origin shall be at least 70% from 1 January 2021.
>
> **By 1 January 2021**, the Commission shall adopt a delegated act in accordance with Article 35 to supplement this Directive by establishing appropriate **minimum thresholds for greenhouse gas emissions savings of recycled carbon fuels through a life-cycle assessment** that takes into account the specificities of each fuel.

In the RED II, which was originally developed for biofuels, two new categories of renewable fuels were introduced: renewable fuels of non-biological origin (RFNBO[2]) and recycled carbon fuels (RCF[1]). However, there is a difference in how those two are counted towards the renewable energy: in contrast to RFNBO which shall be counted to the renewable energy targets, Member States are given the right to decide on whether RCF can contribute to the renewable energy targets (Article 25). Concerns have been expressed that divergent Member State acceptance of RCFs will create a fragmented EU market for this type of fuels and thus create an unnecessary barrier to deployment and delay their market access in the EU [ART Fuels Forum 2020]. Secondly, the Delegated Act on minimum thresholds for GHG emissions savings of RCF deriving from Article 25(2) is still pending, although it should have been adopted by 1 January 2021 already. This creates another barrier to implementation. Commission adoption is now planned for the fourth quarter 2021 [European Commission 2021a].

Article 27: Calculation rules with regard to the minimum shares of renewable energy in the transport sector

> [...]
>
> **By 31 December 2021**, the Commission shall adopt a delegated act in accordance with Article 35 to supplement this Directive by establishing a Union **methodology setting out detailed rules** by which economic operators are to comply with the requirements laid down in the fifth and sixth subparagraphs of this paragraph.

Article 27 of the RED II defines eligibility criteria for sources of electricity to be used for the production of RFNBO. In principle, three options are foreseen: (i) use of a country's electricity mix through grid connection, (ii) use of renewable electricity through direct connection to a power generation installation and (iii) use of renewable electricity through grid connection which is verified by either guarantees of origin (GO) or power purchase agreements (PPA).

Especially option 3 is of high interest to investors, since options 1 and 2 both have certain drawbacks. The use of a country's electricity mix (option 1) is only feasible in very few European countries such as France, Austria, Norway, Sweden and Iceland whose electricity grid mix meets the required GHG emission savings of 70% for the production of e-fuels. The use of renewable electricity through direct connection to a power generation installation (option 2) will require the capacity of the power generation installation to exceed the capacity of the electrolyser, which is undesirable from an economic point of view (adds on CAPEX unless a PPA is established with a contractor). The question whether excess electricity from this power generation installation could be fed into the electricity grid will depend on the exact requirements regarding grid (dis-)connection which are still to be defined.

As depicted in Figure 19, four criteria need to be defined for option 3: renewability, temporal correlation, geographical correlation and additionality. However, the Delegated Act on requirements for renewable electricity deriving from Article 27 of the RED II is still pending and Commission adoption is planned for the fourth quarter 2021 [European Commission 2021b], i.e. shortly before the deadline set in the RED II. This acts a significant barrier to implementation since any decision on large-scale e-fuel projects in the EU will be delayed until these open issues have been clarified.

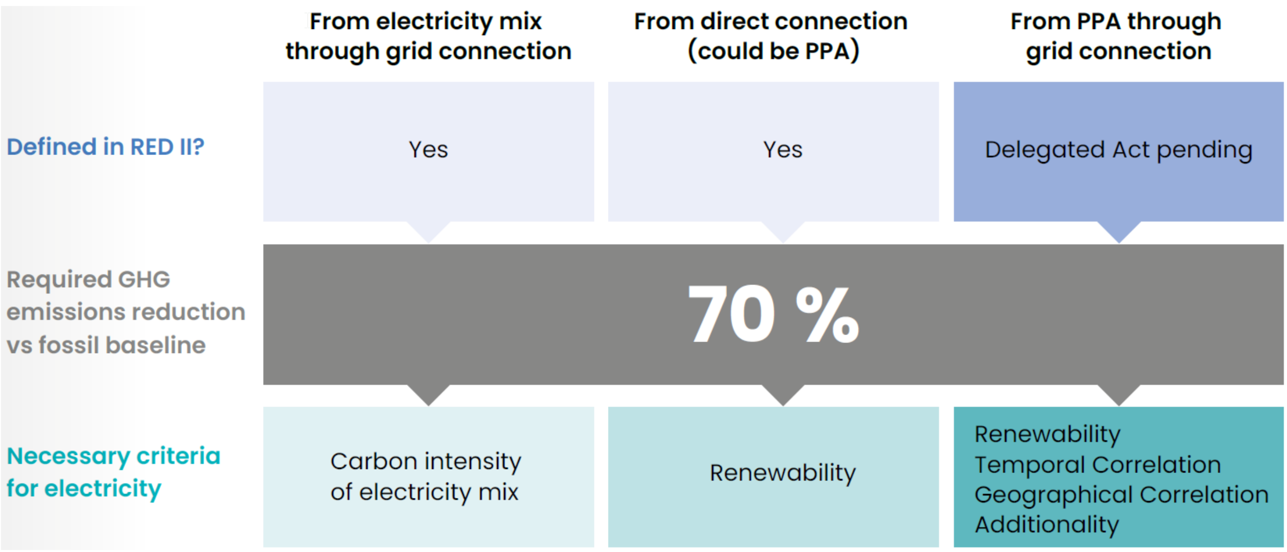

Figure 19: Possible sources of electricity as defined in the RED II [Crone et al. 2020]

Article 28: Other provisions on renewable energy in the transport sector

[…]

5. **By 31 December 2021**, the Commission shall adopt delegated acts in accordance with Article 35 to supplement this Directive by specifying the methodology to determine the share of biofuel, and biogas for transport, resulting from biomass being processed with fossil fuels in a common process, and by **specifying the methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels**, which shall ensure that credit for avoided emissions is not given for CO_2 the capture of which has already received an emission credit under other provisions of law.

[…]

Furthermore, Article 28 of the RED II requires the Commission to adopt a Delegated Act on the calculation methodology for determining the greenhouse gas impact of RFNBO and RCF. This Delegated Act is still pending and Commission adoption is planned for the fourth quarter 2021 [European Commission 2021c], i.e. shortly before the deadline set in the RED II. This acts a significant barrier to both R&D and implementation since this methodology – together with the to-be-defined minimum threshold under Article 25 (see above) – will determine whether or not the eForFuel products would qualify to be counted towards the renewable energy targets. Due to this absence of legislation, a corresponding calculation could not be performed by [Rettenmaier et al. 2021].

Further regulatory frameworks and policies

There is also a link between the above mentioned pending methodology and the European Union Emission Trading System (EU ETS) [European Parliament & Council of the European Union, 2003]. For the fourth phase of the EU ETS, covering the period 2021-2030, a number of important changes were introduced, among others the possibility to support environmentally safe carbon capture and utilisation (CCU) projects under the so-called Innovation Fund (IF). However, there is currently legal uncertainty whether (and/or under which conditions) CO_2 emissions captured by an installation to which the EU ETS Directive applies and transferred to CCU installations should be deductible for the transferring installation. This is especially relevant if the EU ETS Directive does not apply to the receiving installation, i.e. if GHG emissions are transferred from sectors covered by the EU ETS to Non-ETS sectors.

In the RED II, the emissions from the combustion of biofuels are treated as carbon neutral, since the emitted CO_2 had earlier been taken up by the biomass from which they were produced. If e-fuels (RFNBO and RCF) were also to be treated as carbon neutral in the RED II, the environmental burden of the CO_2 feedstock would have to be counted elsewhere, e.g. at the primary emitter. There is a clear risk for an accounting loophole if at the same time deduction was allowed in the ETS sector and e-fuels were treated as carbon neutral. This further legal uncertainty also acts a significant barrier to implementation.

Last but not least, in July 2021, the European Commission released a number of policy proposals in its ‘Fit for 55’ package [European Commission 2021d], aimed at achieving the European Union’s goal of reducing GHG emissions by 55% in 2030 compared to 1990 levels. This package includes a number of elements affecting the transport (fuel) sector, among others an amendment of the RED II [European Commission 2021e]. Since the latter is just a proposal and still subject to a legislative procedure involving the Council of the European Union as well as the European Parliament, the final document might differ significantly. Therefore, we refrain from speculating what the proposed changes would mean for eForFuel.

7. Conclusions, recommendations and outlook

A set of conclusions and recommendations can be derived from the results discussed in the previous chapters to support stakeholders including process developers, scientists and policy makers in improving the socio-economic sustainability of the analysed e-fuels and to inform the public.

7.1. Conclusions

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

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

- The most important social risks are connected to the provision of the very high amounts of electricity needed for the production of e-fuels. Although specific social risks associated with renewable electricity cannot be deduced yet from the most recent available social risk databases, it is expected that electricity provision will remain a social hot spot in the life cycle of e-fuels for decades.
- The enormous amounts of additional renewable electricity generation capacity required to be built up globally in the next decades will bring many socio-economic challenges and chances. This developing market needs to be further analysed, monitored and managed by all involved actors, including industry and politics. Risks are particularly high in countries with less developed public health, social welfare and governance systems. If substantial electricity imports into the EU, e.g. from the Middle East and North Africa (MENA region), are considered for e-fuels, on the one hand high risks arise and a risk management strategy for these countries will be the most important element to ensure socially sustainable e-fuels. On the other hand, good conduct in high risk procurement can lead to great social benefits because decent work and additional income is particularly important in this region. This however also means that suppliers not complying with social standards have to be excluded despite dependencies that may have evolved and higher costs elsewhere.

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


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

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

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

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


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- In this context, it remains to be seen whether another potential barrier related to the regulatory framework will be resolved: the interplay between the EU ETS Directive (Directive 2003/87/EC) and the RED II. This concerns a potential accounting loophole for fossil CO_2 emissions which could lead to neither counting these in delivering sectors such as steel and concrete plants nor in the receiving fuel sector. In case this loophole is not plugged in the sense of avoiding a double omission of CO_2 emissions, this could severely damage the public perception of CCU technologies.

- Last but not least, we have to acknowledge that while still waiting for important bits and pieces of the regulatory framework which is currently in force, new proposals for significant amendments and changes to the latter are already on the table. It remains to be seen which of these proposals survive the upcoming legislative procedure, but it is clear that this transition period does not provide a stable investment climate and rather prevents engagement in large-scale e-fuel projects in the EU.

7.2. Recommendations and outlook

On the basis of the above conclusions, the following recommendations can be made to different stakeholders from a social perspective:

To process developers

The balance of social benefits and risks should be increased by increasing the process efficiency, in particular regarding the following aspects:

- Since most of the social risks are associated with the provision of renewable energy, electricity and heat use in the production process of electro-microbial fuels should be minimised as far as possible. This means first of all maximising the Faraday efficiency and the energy efficiency of the electroreactor, or at least aiming for the values set in our optimal technology development scenario. For this purpose, alternative reactor designs or other electrode materials should be investigated. An additional lever is the yield of the bioreactor, because a large part of the consumed CO_2 is released again in the bioreactor and subsequently recycled. Avoiding this would reduce the electricity demand this creates in the electroreactor. The values of the optimal scenario should be aimed for in this aspect as well. This could be achieved through using alternative metabolic pathways of the bacteria. Furthermore, the product separation step is very energy-intensive. Alternative separation processes should be investigated here. Best possible heat integration should be strived for.

- Efficiency improvements in the use of K_2SO_4 and fermentation media should also be targeted if this does not compromise the electricity use efficiency.

To the Carbon Capture and Utilisation community in general

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- The present study shows that synthetic fuels such as e-fuel and PtX fuels are not socially sustainable just because renewable resources are used for their production. 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 for all products.

- Considering the large amounts of electricity that will be needed for not only for synthetic fuels but also for the defossilisation of other sectors, it seems plausible that either electricity or electricity-based intermediates such as H_2 have to be imported into the EU. The CCU community should start, join or support primarily political initiatives for a socially sustainable future procurement of these new energy carriers.

- Once e-fuel concepts are being upscaled to an industrial level of production, a socially sustainable procurement strategy has to be established also for inputs beyond electricity such as K_2SO_4 and fermentation media in this case. Certifications of suppliers according to standards such as those of the Global Reporting Initiative (GRI) are an important element in this strategy. This is also to the benefit of industrial actors themselves because they are increasingly held accountable for violations of social standards in their supply chains.

- Social acceptance of e-fuels is still largely open. Therefore, honest communication strategies should be implemented, highlighting the strengths of the concept but avoiding any greenwashing and false expectations, especially with regard to the time horizon of possible large-scale production.

To political decision-makers

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- For the direct or indirect electrification of the transport sector, technologies with the highest possible energy efficiency should be preferred in order to minimise associated social risks. These technologies should be supported with priority.
- Even with high efficiency, the electrification of the transport sector and other sectors such as heat and chemicals will foreseeably require enormous additional amounts of renewable electricity. Since this is central to the development towards a simultaneously climate-neutral, competitive and social Europe, an overall concept for future-proof renewable electricity must be developed with very high priority. The project under consideration here is just one of many examples whose future depends, among other things, on such a concept.
- For an overall concept for a reliable, competitive and socially beneficial provision of renewable electricity for Europe, it may be reasonable to include countries from the Middle East and North Africa (MENA region). This could be done by importing energy-intensive intermediate products such as hydrogen, which would only be indirectly relevant for the concept considered here by reducing the pressure on the electricity market, because a long-distance transport of the intermediate formate would hardly be technically feasible in this case.
- From a social point of view, it must be taken into account in the case of a possible future import of electricity from e.g. North Africa that, on the one hand, social risks are higher than in the EU and, at the same time, the influence on them is lower. On the other hand, the possibilities for social improvements are also much higher there. If people in the neighbouring countries were doing better, Europe would also benefit from a stabilisation of the region, among other things because this could mitigate causes of migration. However, seizing this opportunity and adequately addressing existing substantial risks requires reliable cooperation at equal level and is difficult to achieve by individual companies. Among the risks, the focus should be on the resolution of armed conflicts, the legal system of the respective countries, and corruption, which have also emerged as hot spots in this analysis. Here, European policy is required to go new ways beyond previous development cooperation. It will be crucial to respect the needs and choices of local stakeholders and communities because otherwise cooperation with best intentions is likely to be perceived as neo-colonialism. In this context, it is also important to learn from failed initiatives such as Desertec.

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- Social impacts in the EU are foreseeably less existential than they might be in countries outside the EU. Nevertheless, opportunities for the expansion of renewable energies should be used, e.g. through participation of citizens in profits via cooperatives. In addition, a better balance must be found between the interests of, for example, direct neighbours of wind turbines and the population as a whole as users of electricity and electricity-based products, so that resistance from parts of the population diminishes and renewable energies can be further expanded.
- The most significant barriers to implementation result from the legal uncertainty, which is due to an absence of legislation in the context of the Renewable Energy Directive (RED II). Therefore, a number of open issues related to Articles 25, 27 and 28 of the RED II should be resolved with high priority and pending delegated acts should be adopted soon.
- For a sustainable future perspective of e-fuels, it is however most important to create a support scheme that does not contain regulatory loopholes rather than having a regulation in place quickly. In particular, it must be avoided that the interplay between the EU ETS Directive (Directive

2003/87/EC) and the RED II leads to neither counting fossil CO_2 emissions in delivering sectors such as steel and concrete plants nor in the receiving fuel sector. This could severely damage the public acceptance of Carbon Capture and Utilisation technologies.

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

8. Abbreviations

BF	Blast furnace, part of steel plant
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
DAC	Direct air capture
ETS	Emissions trading system (EU scheme for trading greenhouse gas emission rights)
FT	Fischer-Tropsch, process for synthesising higher hydrocarbons
FTE	Full time equivalent
GHG	Greenhouse gas
GMO	Genetically modified organism
GRI	Global reporting initiative
GTAP	Global trade analysis project (provider of economic database)
ILCSA	Integrated life cycle sustainability assessment
LCA	(Environmental) life cycle assessment
LPG	Liquefied petroleum gas
MEA	Monoethanolamine
MENA	Middle East and North Africa (region)
PEM	Polymer electrolyte membrane
PtX	Power-to-X (range of electricity based products including fuels)
PtH	Power-to-heat, heat generated from electricity via various technologies
PV	Photovoltaics
RCF	Recycled carbon fuels
RE	renewable electricity
RED	Renewable energy directive (EU legislation)
RFNBO	Renewable fuels of non-biological origin
SHDB	Social hotspot database
sLCA	Social life cycle assessment
TRL	Technology readiness level

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