Study N°2023-04

Methodological recommendations for LCA of e-fuels and initial calculations

Summary
December 2024

Version 1.0	**17/12/24**	
Editors	**Auditors**	Approver
LORTILLOIS Domitille MAURIN Adrien GAILLARD Marine	NUNES Mike GERAND Yves LEPETIT Cyrille	

The SCORE LCA association is a study and research body dedicated to work on Life Cycle Assessment (LCA) and environmental quantification. Its aim is to promote and organise collaboration between companies, institutions and scientists in order to encourage the shared and recognised development, at European and international level, of the Life Cycle Assessment method and its practical application.

- This work has received support from ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie): www.ademe.fr
- The views and recommendations expressed in this document are those of the authors and, unless otherwise stated, do not necessarily reflect the opinion of the entire SCORE LCA membership.
- The information and conclusions presented in this document have been drawn up on the basis of scientific and technical data and the regulatory and standards framework in force at the date the documents were published.

SUMMARY

1 Background and issues

E-fuels are synthetic fuels made from hydrogen (H_2, via decarbonised electricity) and CO_2 or N_2, for a final product in a liquid state (power-to-liquid, PTL) or a gaseous state (power-to-gas, PTG).

E-fuels make it possible to avoid using fossil fuels directly. They therefore represent an interesting opportunity for both decarbonising the transport sector and strengthening Europe's energy sovereignty.

This technology therefore combines hydrogen and CO_2 (or N_2), making it possible to recover this greenhouse gas emitted by many industries via capture and recovery technologies.

There are many Life Cycle Assessments (LCA) on e-fuels:

- On google scholar, the search "LCA e-fuel" leads to **almost 1,000 results**, and the search "LCA Power-to-X" to **over 23,000 results**.
- Some articles summarise several LCAs carried out, for example (Koj, Wulf, and Zapp 2019) and (Ince et al. 2021).

In the absence of common methodologies**, the conclusions of these LCAs of e-fuels vary enormously**. For example, for e-methanol, LCAs in the literature report cradle-to-gate carbon footprints ranging from **-1.7 to +9.7** kgCO_2 eq per kg of methanol (Müller et al. 2020).

Furthermore, in the article by (Koj, Wulf, and Zapp 2019), the authors analysed 32 Power-to-X LCAs and noted that **the LCAs studied often lacked transparency**, both in terms of the **technology** used and the **LCA methodologies** implemented.

2 Aims of the study

In this context, ScoreLCA commissioned the EVEA (LCA expert) x S3D (alternative fuel expert) partnership to:

- Establish the technological status of 8 e-fuels (study report part 2)
- Identify the technological challenges of e-fuels and the associated LCA methodological issues (study report, parts 3 and 4).
- On the basis of a case study and the literature review, come up with relevant methodological recommendations for LCAs of e-fuels (study report, part 5).

3 State of the art in e-fuels technology

The report presents a review of current knowledge about synthetic fuels (e-fuels), focusing on production technologies, their technological maturity, efficiency and energy consumption, as well as the technical and economic barriers to their adoption.

3.1 Hydrogen production

The production of hydrogen, a crucial initial stage in the synthesis of e-fuels, relies mainly on water electrolysis, a technology whose maturity can be described as commercial. Alkaline electrolysis and PEM (Proton Exchange Membrane) electrolysis are widely used for their performance and adaptability to industrial constraints. However, these processes are inherently electro-intensive, with an electrical efficiency of around 60-75%, depending on the size of the installation. Cooling is required to dissipate the excess heat produced. In addition, hydrogen generally needs to be compressed, to several tens of bar depending on the application, and even hundreds of bar for transport.

3.2 Capture of CO_2

Sources of CO_2 can be of various concentrations: concentrated sources (45%vol. CO_2), such as Steam Methane Reforming off-gases, moderately concentrated sources (8.5%vol. CO_2) such as combustion fumes, or dilute sources (0.04%vol. CO_2) such as in atmospheric air.

Capture technologies include:

- **Chemical absorption**: Using solvents such as MEA (monoethanolamine), this technology is the most mature for CO_2-rich streams. It includes a thermal solvent regeneration stage, which requires heat input.
- **Adsorption and cryogenics**: Appropriate for streams with low CO_2 concentrations, cryogenics enable high product purity to be achieved, but remain costly in terms of energy consumption.
- **Direct Air Capture (DAC)**: This technology enables CO_2 to be captured from the atmosphere, but its cost and energy consumption remain a barrier to large-scale industrial use.

3.3 Synthesis of specific fuels

Each type of synthetic fuel - e-methanol, e-kerosene (e-SAF), e-diesel, e-DME and e-gasoline - requires specific processes that influence yields and costs.

- **E-Methanol**: Synthetic methanol is produced by catalytic reduction of CO_2 with H_2 with a net yield of 82%. This fuel is particularly used in industrial sectors and as a base for other chemical syntheses.

- **E-kerosene (e-SAF)**: produced by Fischer-Tropsch synthesis or via the conversion of methanol into distillates, e-kerosene is intended for the aviation sector. It must meet strict safety standards such as ASTM D7566, which allows it to be blended with up to 50% conventional paraffin. The Fischer-Tropsch process is 76% efficient, but the reaction requires a lot of energy to compress and heat the reactants (CO_2 and H2).
- **E-Diesel**: also produced by Fischer-Tropsch, it can be blended with fossil diesel. It complies with the EN 15940 standard, making it compatible with diesel engines without requiring any modifications. Net efficiency is 88%.

- **E-gasoline**: this production route is equivalent to the production of e-kerosene, with the addition of further treatment to generate lighter hydrocarbons. Synthetic petrol complies with European EN 228 standards, and can be used in conventional engines. It requires a lot of energy to produce, particularly electricity to compress the reagents, and its net yield is around 85%.

- **E-DME (dimethyl ether)**: produced mainly by dehydration of methanol, DME is considered a viable alternative to LPG and diesel, thanks to its clean combustion properties and absence of fine particles in the exhaust. For fuel use, DME is used in a mixture with LPG in the same engines as petrol engines, or in a mixture with diesel. Production efficiency is around 90%.

3.4 Electricity consumption and surplus heat

Each type of synthetic fuel requires a high level of electricity consumption, particularly for compression upstream of the thermochemical reactions. For example, the production of e-kerosene by Fischer-Tropsch requires around 0.528 kWh/kg, and that of e-diesel reaches similar levels. As for the thermal integration of these production processes, some reactions are exothermic, so the excess heat is generally recovered, contributing to the energy efficiency of the installations.

3.5 Maturity and development challenges

Technologies for producing e-fuels are at different levels of maturity (TRL). The production of methanol and hydrogen by electrolysis is close to large-scale industrial adoption. However, certain routes, such as DAC for the capture of atmospheric CO_2 or the conversion of CO_2 into olefins, require further progress before they can be deployed commercially. High production costs are the main obstacle to the deployment of these alternatives.

3.6 Outlook and projects

Pilot projects in Europe (e.g. the Sunfire plant in Germany) and the United States are showing a growing interest in e-fuels. Regulations are encouraging this adoption in the aviation and maritime transport sectors, where green alternatives are limited. IRENA forecasts that global demand for methanol will reach 500 Mt by 2050, and that synthetic fuels will account for a growing share of the energy mix for transport.

3.7 Technological comparison of different e-fuels

	Methane		Methanol	Ammonia	Gasoline		Diesel	DME		SAF	
	Catalytic	**Biological**	**Catalytic**	**Haber Bosch**	**FT**	**Methanol pathway**	**FT**	**Syngas to DME**	**Methanol to DME**	**FT**	**Methanol pathway**
Maturity	TRL 9 : Mature and commercialized	TRL 7 : Industrial demonstrator	TRL 7-8 : Late-stage demonstration/ early steps industrialization	TRL9 : Well-developed technology regarding conventional production	FT : TRL 9 RWGS : TRL 7	MTO : TRL 9 Nowadays commercialized by Haldor Topsoe & ExxonMobil	FT : TRL 9 RWGS : TRL 7	TRL 5 – 6 Less mature than MeOH to DME	TRL 6- 7 Expected for 2030	FT : TRL 9 RWGS: TRL 7	MTK : TRL 9 Nowadays commercialized by Haldor Topsoe & ExxonMobil
Storage / Distribution	Compression or liquefaction		Gas Station in China (M100)	Stored at -33°C-Transport by Ship-Truck	Existing infrastructures		Existing structures	Existing structures		Existing structures	
Market	Existing vehicles and market		Combustion car. + chemical tankers	Not yet developed	Existing vehicles and market	Existing vehicles and market	Existing vehicles and market	Not yet developed		Existing vehicles and market	
Catalyst	Ni, Ru, Rh	N A	Cu,Zn, Alumine	Fe_2O_4-Fe/AL_2O_3-KOH	RWGS FT	Methanol to Olefins	RWGS FT	Bifunctional catalysts	γ Alumine	RWGS FT	Methanol to Olefins
Heat prod. / cons.	Exothermic	Exothermic	Exothermic	Autothermic	Exothermic	Exothermic	Exothermic	Exothermic	Endothermic	Exothermic	Exothermic
P, T op. conditions	10 to 15 bar 250 to 400°C	< 10 bar 20 to 60°C	50 to 100 bar 250 to 300°C	100 to 300 bar 300 to 550°C	10 to 60 bar LT : 190-250°C HT : 320–350°C	15 to 20 bar 300 to 400°C	10 to 60 barLT : 190-250°C HT : 320–350°C	15 to 20 bar 300 to 400°C	10 to 12 bar 290 to 400°C	10 to 60 bar LT : 190-250°C HT: 320–350°C	15 to 20 bar 300 à 400°C
Electricity	CH4 synthesis 0.320 kWh/kg	CH4 synthesis 0.320 kWh/kg	MeOH Synthesis 0.276 kWh/kg	NH3 synthesis 0.585 kWh/kg	Gasoline synthesis 0.526 kWh/kg	Gasoline synthesis 0.827 kWh/kg	Synthetic diese l0.528 kWh/kg	Non connu	MeOH to DME 0.0022 kWh/kg	SAF Synthesis 0.528 kWh/kg	SAF Synthesis 0.832 kWh/kg
Coproducts	N A	N A	Eau	N A	Diesel (28%) / Kerosene (32%) / LPG (3%)	LPG (19%) / gas (1%)	Gasoline (37%) / Kerosene (32%) / LPG (3%)	Water	Water	Gasoline (37%) / Diesel (28%) / LPG (3%)	Diesel (65%) / LPG (8%) / gas (2%)

4 Methodological challenges for the LCA of e-fuels

According to the bibliography, the major challenges for LCA of e-fuels are:

- Assessing **the sources of electricity** used to manufacture hydrogen,
- The **methodology used to take account of** CO_2 as a raw material,
- And, to a lesser extent, **the type and efficiency of the electrolyser**.

In this summary, we will mainly focus on these 3 points.

In the study report, the methodological state of the art is broken down into 2 main parts:

- The state of the art of available data for carrying out LCIs (part 3 of the study report)
- The methodological challenges of e-fuels, illustrated by a case study and recommendations (part 4 of the study report)

4.1 State of the art of available LCI data

The state of the art of available data details the LCIs available for modelling:

- CO_2 capture process with or without pre-treatment of the CO_2 fumes and with or without downstream purification of the CO_2
- transport of CO_2 in the form of compressed gas (by pipeline) or liquefied gas (by truck/train/refrigerated ship).
- electrolyser infrastructure
- tank filling phase
- e-fuel combustion.
- modelling electricity sources.
  This point presents a particular challenge for the LCA of e-fuels: the consumption of electricity by the electrolyser to produce dihydrogen is one of the main sources of impact. It is therefore particularly important to ensure the robustness of the following data:
  - Quantity of electricity consumed by the electrolyser
  - Electricity mix used
  - Inventories of electricity generation and transmission facilities.

The recommendations on the choice of these data are as follows:

Data	Recommendation
Quantity of electricity consumed by the electrolyser	1. Use **specific data** whenever possible, 2. Failing that, use **bibliographic data**, paying particular attention to the **technological representativeness** of the data used.
Electricity mix used	1. Use **specific data** where possible (dedicated electricity production, contract with a supplier that guarantees a certain mix) 2. When using electricity from the grid, use **the most up-to-date data possible.** In France, RTE gives the most up-to-date generation mix (to which imports and exports should be added to arrive at the desired consumption mix). 3. **Avoid using secondary data from databases**, which may be less up-to-date than data from other sources.

Inventory of electricity generation and transmission facilities	1. If possible, use **specific data** (dedicated production) 2. Where appropriate, **the ecoinvent LCA database** provides secondary data with excellent geographical representativeness and good technological representativeness, but limited temporal representation.

How green electricity certificates are taken into account in LCA is described in detail *in* the SCORE LCA study "*Geographical electricity mix vs. market electricity mix: what recommendations for LCA?*

4.2 Methodological challenges of an e-fuel

An LCA of e-fuels must follow the 4 main phases of an LCA defined by ISO 14040 and ISO 14044, i.e.: objectives and scope of the study, life cycle inventory, impact assessment and interpretation of the results.

4.2.1 OBJECTIVE

The objective of the study must detail the application envisaged, the reasons for carrying out the study, the audience concerned and the communication envisaged.

Table 1 Recommendations concerning the purposes of LCA

Aims of LCA	Example of a reason for carrying out an LCA
Eco-designing an e-fuel	Comparing the environmental impact of different e-fuel systems Comparing variants of an e-fuel system
Ensuring the environmental benefits of e-fuel Communicating the environmental benefits of e-fuel	Compare the environmental impact of an e-fuel with a reference solution (fossil fuel, CO_2 emissions to air or another energy storage system).
Communicating the environmental impact of e-fuel	Calculate the environmental footprint of an e-fuel to communicate with external partners

4.2.2 SCOPE OF THE STUDY

The scope of the study must include details of:

- The product system to be studied: function, functional unit and reference flow
- System boundaries: perimeter, system description and cut-off rule
- Managing the system's multifunctionality

4.2.2.1 Product system to be studied

The functional unit, according to ISO 14044, quantifies the function(s) of the system, and is "the quantified performance of a system intended to be used as a reference unit".

The choice of **functional unit** varies according to the objectives of the LCA. In the case of e-fuels, the following functional units may be relevant:

Table 2 Recommendations for functional units based on the different LCA objectives

Purpose of LCA	**Objective of the LCA**	**Type of functional unit**	**Examples of functional units**
Ensuring the environmental benefits of e-fuel Communicating the environmental benefits of e-fuel	Compare fuels with the same composition and physico-chemical properties	Energy content	Produce 1 MJ PCI of fuel Produce and use 1 MJ ICP of fuel
	Compare fuels with different compositions or physico-chemical properties (yield, etc.).	Energy services	Travelling 100km in an average vehicle in France in 2024 Transporting 1 tonne of goods over 1 km in France by 2024 Travelling 1000km with a category X aircraft
	Compare CO_2	Multifunctional units	Treating 1kg of CO_2 from an industry AND supplying X MJ of fuel
	Compare energy storage processes	Multifunctional units	Draw 1 MW from the electricity grid for 1 hour AND supply X MJ of fuel
Eco-designing an e-fuel	Comparing the environmental impact of different e-fuel systems Comparing variants of an e-fuel system	Energy content	Produce 1 MJ PCI of fuel Produce and use 1 PJ PCI of fuel
Communicating the environmental impact of e-fuel	Calculate the environmental footprint of an e-fuel	Energy content	Produce 1 MJ PCI of fuel Produce and use 1 PJ PCI of fuel

4.2.2.2 System boundaries

The system boundaries include the perimeter of the system, a description of the system with a flow diagram and a description of the cut-off rules.
The perimeter breaks down into 3 components: the "life cycle stages" perimeter, the temporal perimeter and the geographical perimeter.

4.2.2.3 Lifecycle stages" perimeter

Fuel producers use specific terminology to express the life cycle stages taken into account in their LCAs:

- Well-to-Wheel for any LCA that takes into account the entire life cycle. This expression is equivalent to Cradle-to-Grave, given that the use and end-of-life phases are merged in the case of a fuel.
- Well-to-tank when the fuel use/end-of-life phase is excluded. It corresponds to the expression Cradle to Custumer gate in traditional LCAs. Well-to-Pump is also sometimes used to designate the same stages.

The following table illustrates these terminologies:

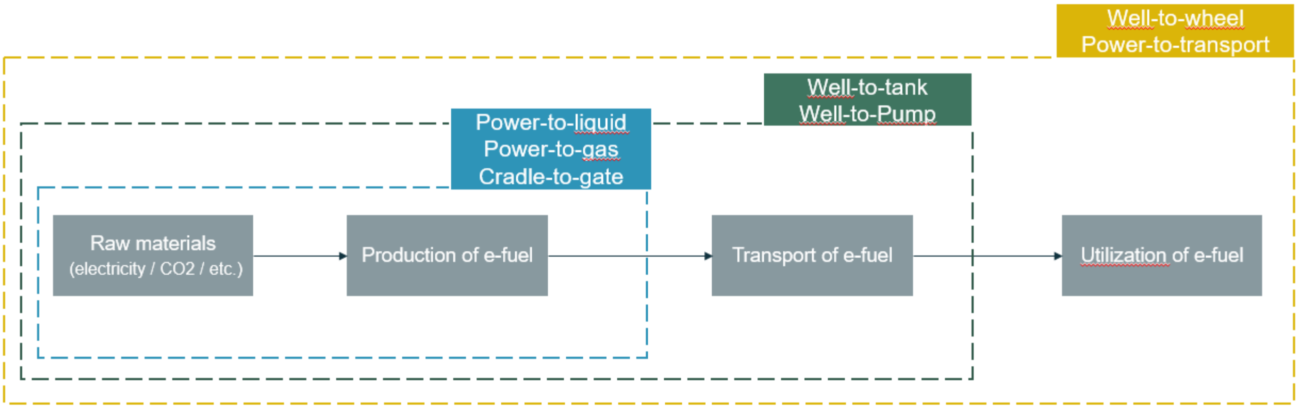


Figure 1 Common terminology used to express the stages of the life cycle taken into account in an e-fuel LCA.

In addition, when electricity is converted into another product, the following terminologies are also used:

- **Power-to-gas:** gaseous fuel made from electricity, considered on a Well-to-Tank life cycle,
- **Power-to-liquid:** liquid fuel made from electricity, considered on a Well-to-Tank life cycle,
- **Power-to-transport:** liquid or gaseous fuel considered in the Well-to-Wheel life cycle,
- **Power-to-chemicals**: chemical products made from electricity, considered on a cradle-to-gate or cradle-to-custumer gate life cycle. Out of scope for e-fuels.
-

Power-to-X: An expression often used to sum up all the above possibilities.
An e-fuel and its fossil equivalent generally have different chemical compositions, so it is necessary to consider the usage phase in order to account for the differences in combustion emissions.

Table 3 Recommendation on the choice of life cycle stages to be taken into account

Lifecycle stage	**Recommendation**
Raw materials	Always take into account
Manufacture	Always take into account
Distribution	To be taken into account: - If the aim is to calculate the footprint over the entire life cycle - For any comparison where the distribution channels are different between solutions In all other cases, do not take into account
Usage/Combustion	To be taken into account: - If the aim is to calculate the footprint over the entire life cycle - For any comparison where the compositions or physico-chemical properties are different between solutions In all other cases, do not take into account
Infrastructure	It is recommended that infrastructure, such as water electrolysis systems to produce H_2, etc., be considered in the inventory to assess the impact of the metals used in such infrastructure.

4.2.2.4 *Time scope*

An LCA can be present or prospective (2030, 2040, 2050, etc.). This last point is dealt with specifically in the Score LCA study "Practical recommendations for prospective LCA/references and examples in the energy field".

4.2.2.5 Geographic scope

A good practice is to define a geographical perimeter at business unit level (e.g. France).

4.2.2.6 System description

It is advisable to describe the boundaries of the system in the form of a diagram.

In an e-fuel LCA, the description of the system must include the following elements, among others:

- Concerning CO_2 or N_2 used as raw materials:
    - **The origin of the** CO_2 / N_2 (DAC, CCU power plant, CCU cement plant, CCU ammonia plant, CCU with carbon of biogenic origin, etc.).
    - The **capture and purification technology** used
    - If a flue gas pre-treatment stage is required with CO_2 capture.
    - The type of CO_2 transport
- About the electrolyser:
    - The **type of electrolyser** (PEM, AEL, SOEC, or other),
    - Whether or not the **oxygen** co-produced **is recycled**, and if so how
    - The origin of the electricity: electricity mix, with or without a guarantee of origin for all or part of the electricity from renewable sources.
- Description of how e-fuel is made
- Depending on the scope of the LCA, the description of the fuel distribution system
- Depending on the scope of the LCA, the description of **use:**
    - The categories of vehicles and engines that will be able to use e-fuel,
    - The conditions of use (for example, whether blending with conventional fuel is necessary before use).

4.2.2.7 Cut-off rules

Conventional LCA rules apply. In particular, the PEF recommends a 3% cut-off rule for mass, energy and environmental impact.

4.2.2.8 Managing multifunctionality

The vast majority of e-fuels (excluding DACC) use CO_2 captured from a plant that first produces another product (electricity, cement, ammonia, etc.). In the current situation, CO_2 fumes are emitted into the air and are therefore similar to waste (zero economic value). However, once the CO_2 from these fumes has been captured, the captured CO_2 can be used as a raw material. As e-fuel production grows, this CO_2 becomes a resource, a raw material that can be recycled. In this sense, the plant from which this CO_2 is derived can be seen as a plant that produces both a main product (electricity, cement, ammonia, etc.) AND, secondarily, the CO_2 that is subsequently used in e-fuels. The plant is then a **multifunctional** system **(treating the end-of-life** CO_2 **and then using it to manufacture a new product)**.

So the question is: **how can we manage the multifunctionality of the** CO_2 **production plant?** In other words, how can the environmental impact be shared between the upstream plant and the e-fuel manufacturer?

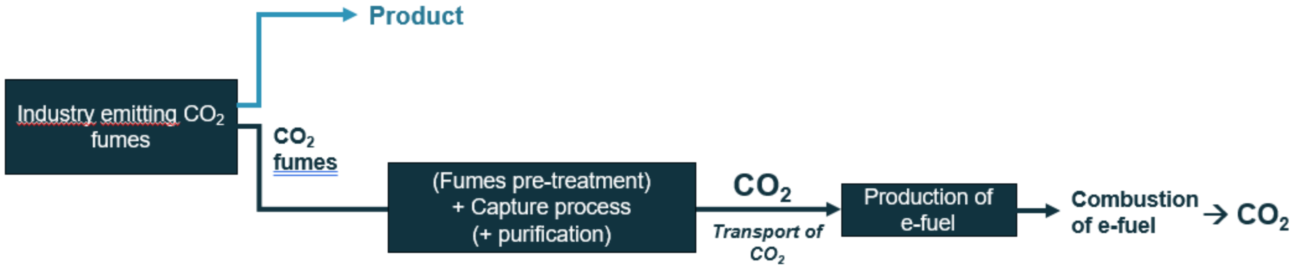


Figure 2 Diagram illustrating the multifunctionality between the two industries and life cycles

For the electricity producer and the e-fuel producer, e-fuel is a **CCU** (Carbon Capture and Utilization), the **purified** CO_2 has a **value**. It is not a waste product that needs to be processed, but a raw material that can be recycled. Pure CO_2 (or at a sufficiently high concentration) is therefore a co-product.

To manage multifunctional systems, ISO14044 recommends several methodologies that can be applied in the case of e-fuel LCAs. These are, in order of priority:

1. Extending the boundaries of the system,
2. The subdivision,
3. Allocations.

Other standards mention other methodologies, which combine the previous ones and which may prove relevant in the case of e-fuel LCAs:

- Extension / substitution (amendment A2 to ISO 14044)
- Substitution / allocation (PEF Circular Footprint Formula method).

At present, there is no consensus on the most appropriate methodology to apply in the context of e-fuel LCA, yet this is a **key** issue **in e-fuel LCA**: it is one of the 2 most influential parameters in the results of an e-fuel LCA.

In the paragraph below, each methodology is briefly explained.

- **Extending the boundaries** involves extending the boundaries of the system to include e-fuel AND the main product of the plant emitting CO_2 fumes.

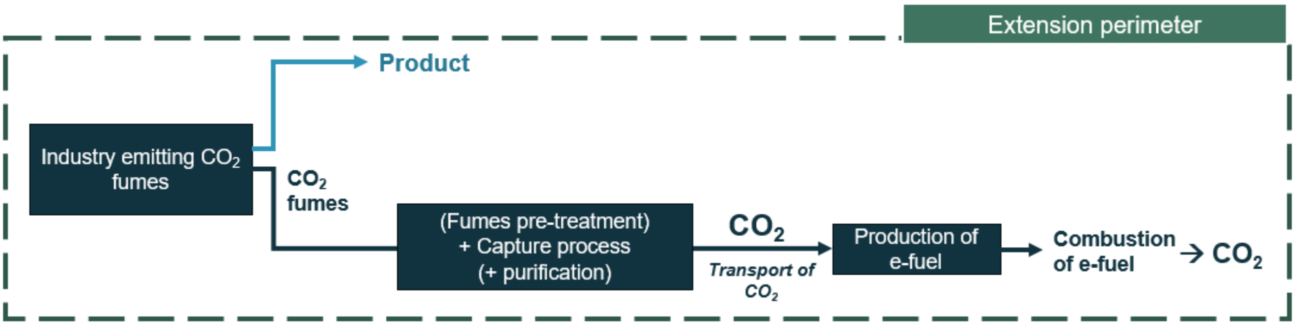


Figure 3 Simplified diagram illustrating the extension of borders

- **Subdivision** is inapplicable in the context of CO_2 production. It consists of subdividing the extended perimeter between the Product and the fumes containing the CO_2 and specifying the inventory flows associated with each part.

- **Allocation** involves distributing the impacts of the multifunctional system between the two life cycles on the basis of the underlying physical relationships between them.

The allocations are difficult to apply to UCCs because finding a relevant physical relationship between the Product and the CO_2 is complicated by the nature of the CO_2 (stable, so zero PCI [energy allocation], contained in flue gases, so no economic value [economic allocation]).

- The cut-off method is a type of allocation: 100% of the impacts of CO_2 capture are attributed to e-fuel, and 0% to the plant emitting the CO_2 fumes.

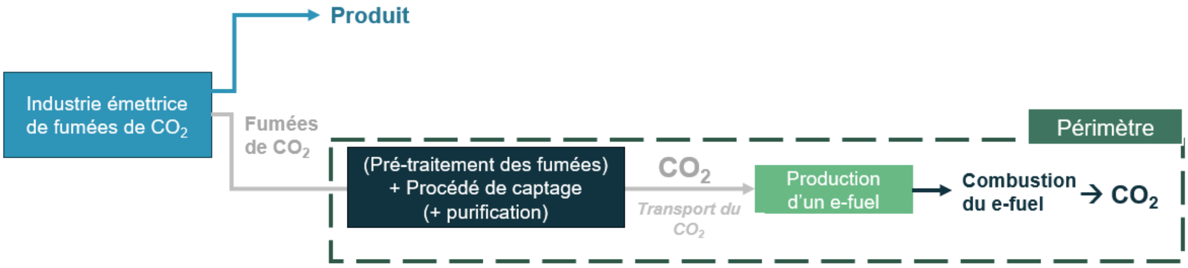


Figure 4 Simplified diagram illustrating the inventory method

- The **extension-substitution method** consists of:
  1. Extension: The "e-fuel" system is extended to become a "CO_2 fume-emitting industry **with CCU system and e-fuel production**" system.
  2. Substitution: This extended system is replaced by the **initial** system **"**Industry emitting CO_2 fumes **without CCU**".

The result is an isolated e-fuel system.
The ScoreLCA study on UCCs and SCCs explains this methodology in detail (SCORE LCA 2021).

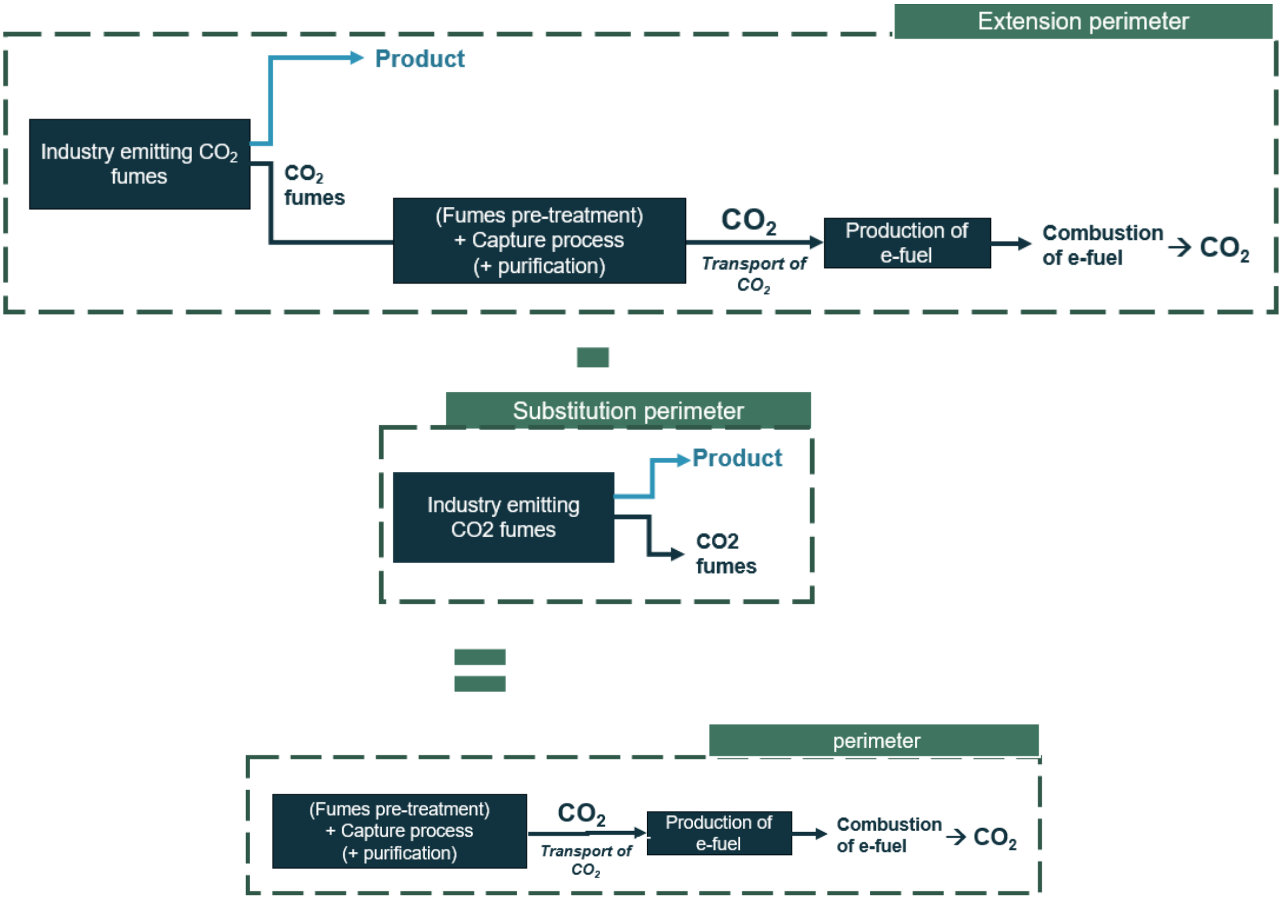


Figure 5 Diagram illustrating extension - substitution

Note: In the case of UCCs where capturing CO_2 **does not modify the multifunctional system process,** the extension-substitution method is simplified.
Only the following inventories remain:

- The e-fuel production (and use) inventory as such
- Inventory of the capture process
- A negative flow of CO_2 fume emissions, corresponding to fume emissions captured to extract the CO_2

NB: changes in the industry emitting CO_2 fumes as a result of the addition of a CCU system should be taken into account as far as possible (availability of associated inventory data).

- The **Circular Footprint Formula (CFF)** defined and recommended in the European Commission's Product Environmental Footprint (PEF) is a methodology combining the allocation and substitution of impacts.

The European Commission's position on the methodology for taking account of UCCs is clear: **for all UCCs, the CFF should be used** because UCC is a type of recycling: the recycling of CO_2 into a product. The CO_2 fumes emitted by the plant have no economic value, but the captured CO_2 does: the CO_2 fumes are therefore a **waste product**; capturing the CO_2 and transforming it is a **recycling process**.
The useful CO_2-based product is called CFF's "substitution point". It corresponds to the 1er input that replaces an equivalent product in a conventional process, i.e. e-fuel that replaces a conventional fuel. The recycling process therefore most often corresponds to the recycling of CO_2 fumes into e-fuel.
In the case of concentrated sources of CO_2 fumes (e.g. an ammonia plant), as the CO_2 fumes are pure, they are considered a co-product and not a waste to be recycled.

No bibliography has applied the SBB to UCDs, only a research document from the Joint Research Center explains the theory.

In the report and for the case study, we have applied the CFF to e-fuels.

Below is a table summarising the different methods of managing multifunctionality, together with a decision tree.

	LCA standards and benchmarks	Data collection?	Can LCAs be added together?	Taking into account the origin of the CO_2 ?	Results e-fuel/ dissociable product	Robustness	Reference to the report
EXTENSION	ISO14044, n°1	Important (factory + CCU)	NA	YES	NO	Strong	P83
EXTENSION-SUBSTITUTION	ISO14044, amendment A2	Important (factory + CCU)	NO	YES	YES	Strong	P85
SIMPLIFIED EXTENSION-SUBSTITUTION	Extrapolation of the extension-substitution method	Satisfactory (CCU)	NO	NO *(except biogenic vs fossil)*	YES	Average *(because it is assumed that CO_2 capture does not affect the plant process)*	P85
SUBDIVISION	ISO14044, no. 2	Not applicable to CCUs					P89
ALLOCATION	ISO14044, no. 3	Important (factory + CCU)	YES	YES	YES	Low	P89
ALLOCATION: Stock method	ISO14044, n°3 (100:0 allocation)	Satisfactory (CCU)	YES	NO	YES	Low	P89
SBB	PEF	Satisfactory	YES	YES	YES	Low	P92

		(CCU)					

Figure 6 Summary table of different multifunctionality management methods

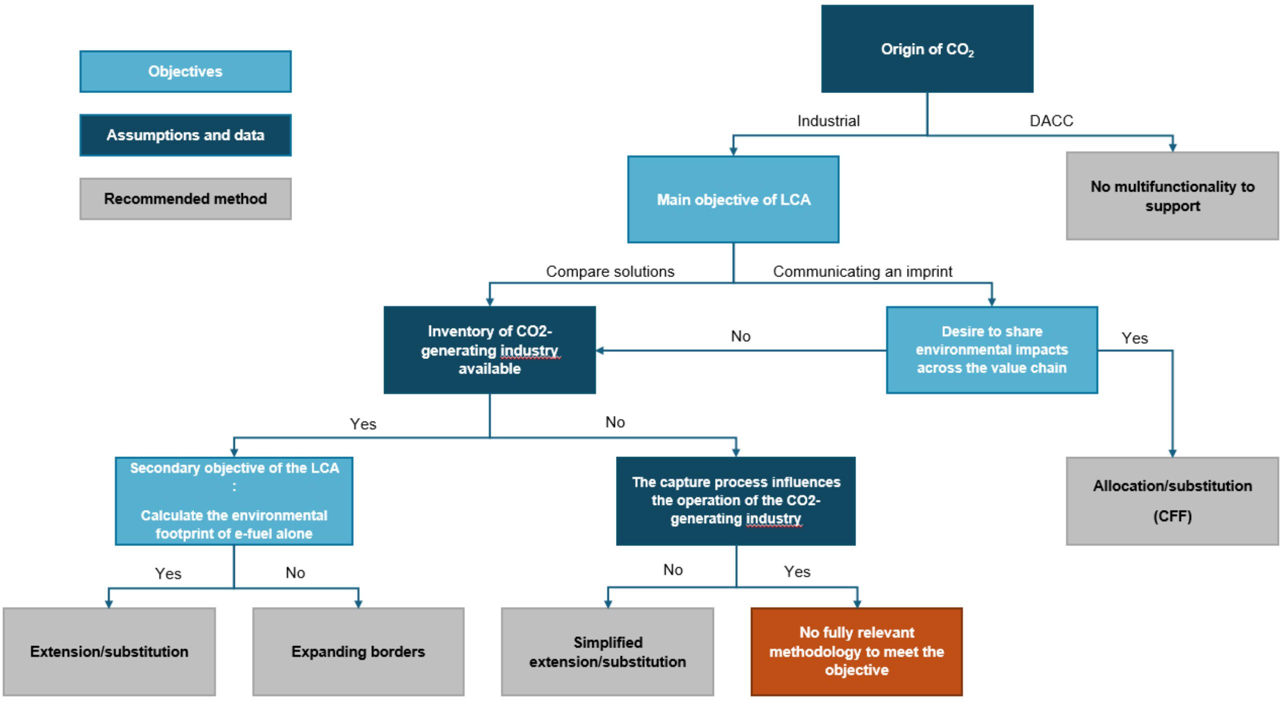


Figure 7: Recommendations for choosing a system multifunctionality management methodology

4.3 Choice of impact indicators

It is recommended that the PEF method be used to select impact indicators, and that the following indicators be added, as they correspond to environmental issues identified for e-fuels:

- Climate change
- Depletion of fossil fuels
- Depletion of mineral and metal resources

Finally, it is recommended that at least one **additional flow indicator** be used, characterising the energy efficiency of e-fuel production. An example of a complementary indicator in this category is:

$$Energy\ efficiency = \frac{PCI\ energy\ content\ of\ the\ e-fuel}{Quantity\ of\ energy\ consumed\ at\ all\ stages\ of\ life\ cycle\ of\ the\ e-fuel}$$

4.4 Other issues

4.4.1 BIOGENIC CARBON

By taking biogenic carbon into account, it is possible to differentiate between the biosourced origin of CO_2 (e.g. from a biorefinery) and the petrosourced origin of CO_2 (e.g. from a cement plant or coal-fired power station). Whether of biobased or petrobased origin, e-fuel only makes it possible to "delay" the emission of CO_2 from the upstream plant - this will be re-emitted when the e-fuel is burnt - but does not make it possible to store the emission from the upstream plant (there is storage from a product life of 100 years). The report details the procedure for differentiating between biobased and petrobased CO_2.

4.4.2 PROSPECTIVE LCA

One of the advantages of e-fuels is that they make the most of electricity generated from renewable sources. These energy sources are gradually being developed to meet the objectives of the energy transition. For this reason, a forward-looking approach to the e-fuels sector is interesting. The SCORE LCA study number 2015-07 sets out the best practices to be implemented.

4.4.3 CONSEQUENTIAL LCA

The impact of e-fuels varies according to the electricity mix and the technologies used. The future electricity mix depends on the country's energy policy. Consequential LCA makes it possible to include possible changes linked to a political decision, for example, from which Power-to-X systems will benefit or which will be initiated by Power-to-X systems.

4.4.4 DYNAMIC LCA

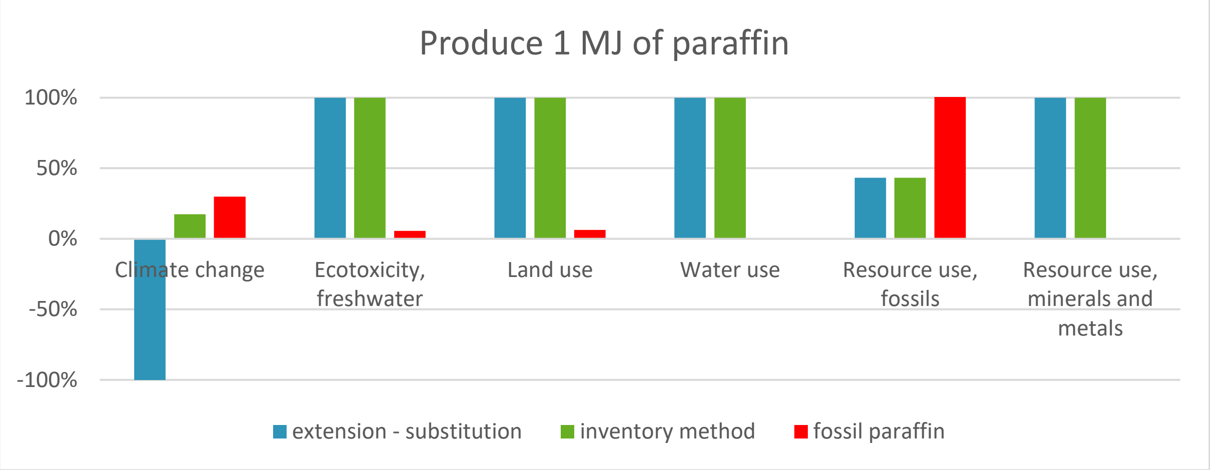
An LCA can be dynamic in 2 ways:

- Or it can be dynamic by modelling its inventory: step-by-step modelling, for example, taking a mix of electricity consumption hour by hour, or year by year over the lifetime of the installations. This type of dynamic LCA takes into account the temporal nature of e-fuel production.
- Or it can be dynamic, by characterising the impacts resulting from the inventory (dynamic or not): for example, CO_2 emitted immediately and CO_2 stored and then emitted 20 years later will not have the same impact on climate change. This type of dynamic LCA takes into account the temporality of emissions.

5 Conclusions from the case study

The methodological issues mentioned above are illustrated by a case study: e-kerosene in a well-to-tank perimeter, using wind-generated electricity. This case study follows on from the case study presented in the SCORE LCA study *"LCA benefits and limitations for the assessment of CCS and CCU"*.

5.1 Influence of multifunctionality management



<u>All methodologies</u>: Depending on the methodology used, the results for e-kerosene are very different, particularly in terms of climate change.

<u>Extension-substitution:</u>
The results are negative in terms of climate change, because the impacts associated with the plant emitting CO_2 fumes with an e-fuel CCU are lower than the impacts of the plant emitting CO_2 fumes without a CCU.
Pre-treatment of CO_2 flue gases before capturing the CO_2 enables the pollutants contained in the flue gases to be eliminated and the CO_2 to be isolated. This results in a reduction in the impact on climate change and the indicators associated with these pollutants compared with the stock method. This is because, unlike the extension-substitution method, the stock method does not take into account the advantages of CCU, i.e. the capture of gases before they are emitted into the air.

<u>Stock method</u>: the stock method produces higher impact results than the extension-substitution method in our example because it attributes the entire CO_2 capture process to e-fuel production, without compensation.
In effect, extension/substitution assigns the entire CO_2 capture process to an offset (emission substitution).

<u>Comparison with fossil fuel</u>: Fossil paraffin has a greater impact than e-fuel on climate change and on the use of fossil resources for all methods.

<u>Boundary extension</u>: With the boundary extension, the functional unit is changed to "Produce 1MJ of e-kerosene and 0.10 kWh of electricity", so this methodology is not comparable with other methodologies whose functional unit is "Produce 1MJ of e-kerosene".
However, thanks to this "extended" functional unit, it is the only methodology (with its variants such as extended substitution) that reflects the fact that the impacts of the electricity from the coal-fired power station are also reduced by using the CO_2 emitted.

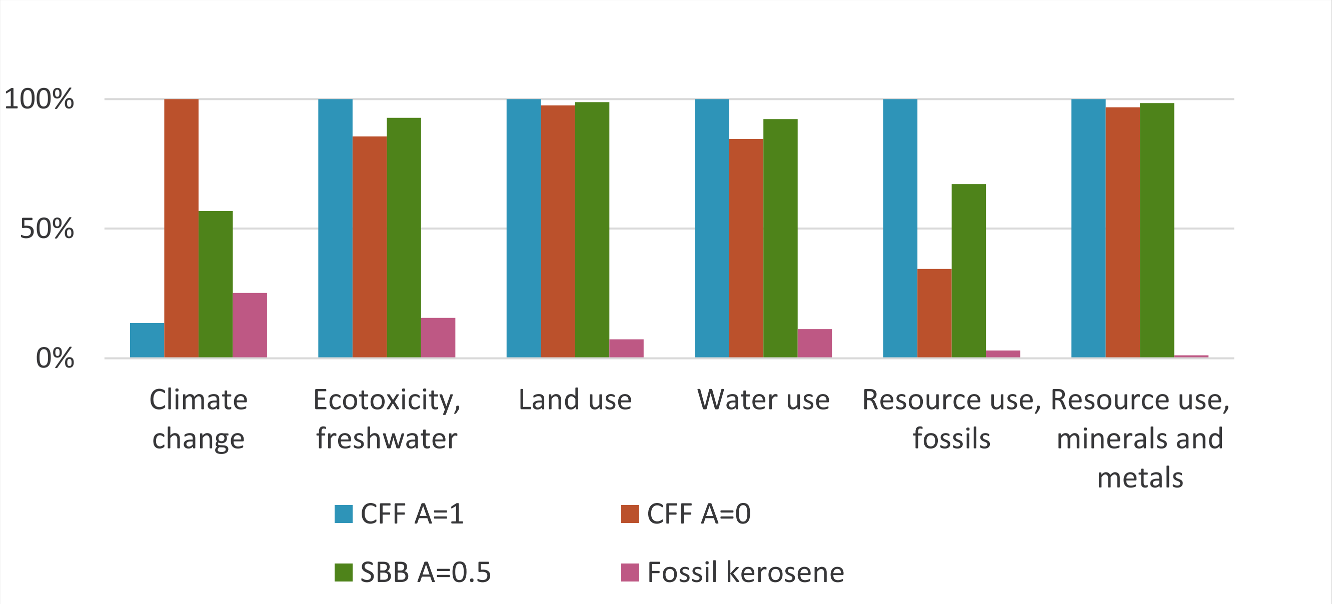
5.2 Influence of multifunctionality management: focus on CFF

In the case studied, the point of substitution chosen is concentrated CO_2: the recycling process extends from the CO_2 fumes to the concentrated CO_2, the CO_2 fumes being the waste to be recycled. The virgin material is therefore a CO_2.

When A=1, the CFF is equivalent to the stock method, and when A=0, it is equivalent to taking into account 100% of CO_2 emissions to air instead of the capture process.

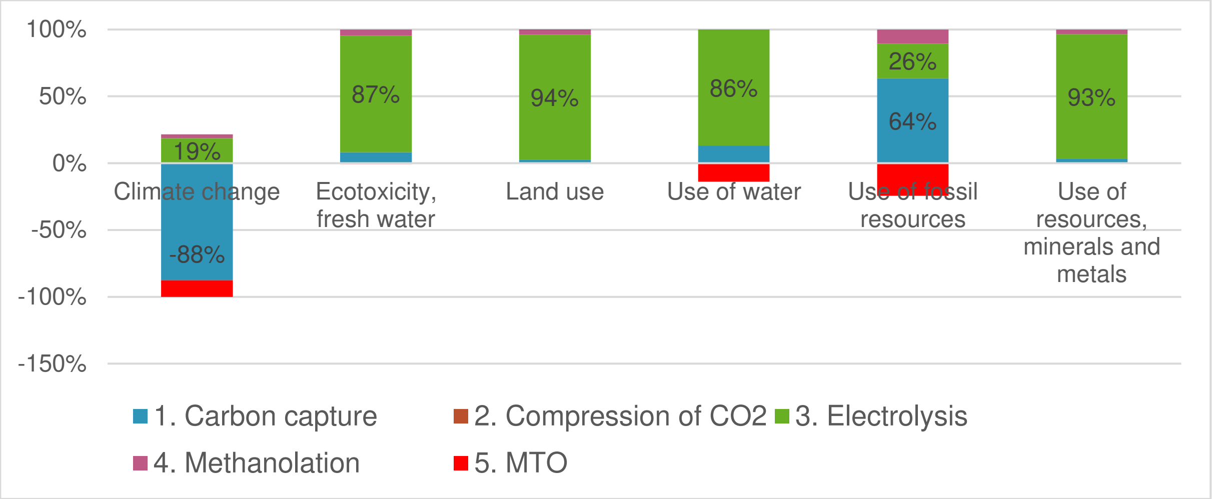
An air emission of 1kg of CO_2 has 20X more impact than 1kg of CO_2 captured and concentrated. With CFF with A=0.5, e-fuel is responsible for 50% of the impact of CO_2 capture and 50% of CO_2 emissions, which is why CFF with A=1 (= the stock method) has less impact than CFF with A=0.5.

The CO_2 producer takes credit for 50% of the impact of CO_2 capture and avoids 50% of CO_2 emissions into the air.
As an alternative, we could also model a SBB with A=0.2 and A=0.8, but this would give a linear evolution of the impact results on the graphs without any major surprises.



The results vary significantly depending on the parameters chosen for applying the CFF method.

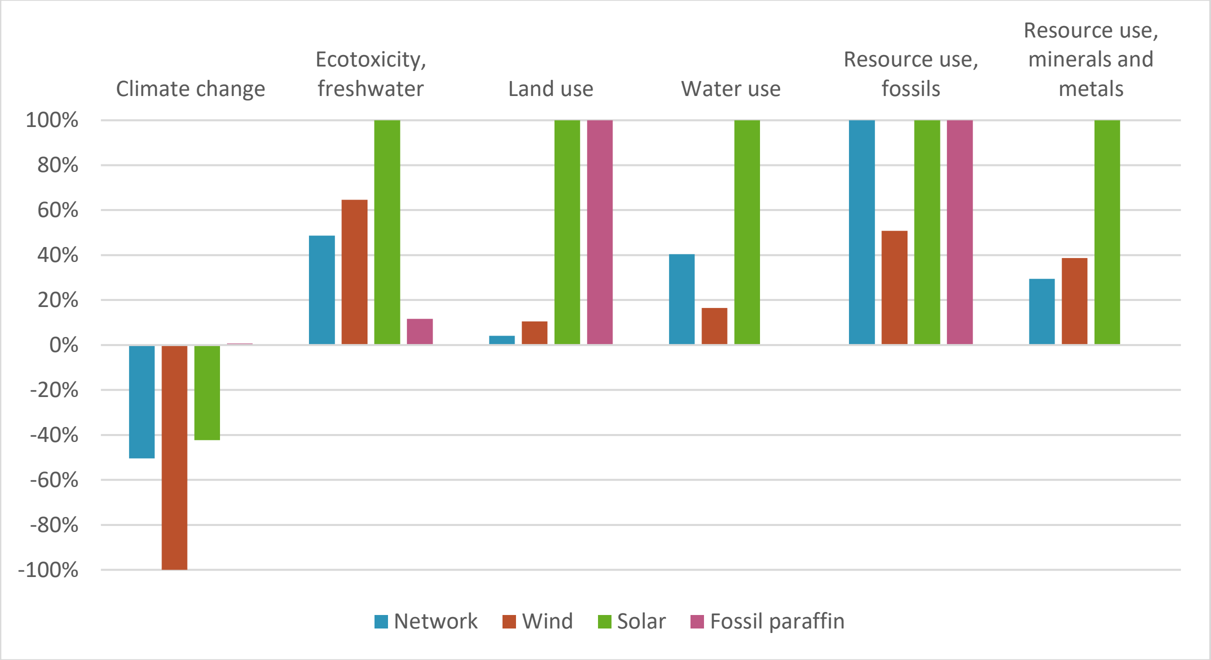
5.3 Main contributors by stage using the extension-substitution method



The main contributor to the impact is electrolysis, and wind-generated electricity in particular, on almost all the indicators.

On climate change and fossil resources, the main contributor is the carbon capture stage (linked to substituted CO_2 emissions and grid electricity respectively).

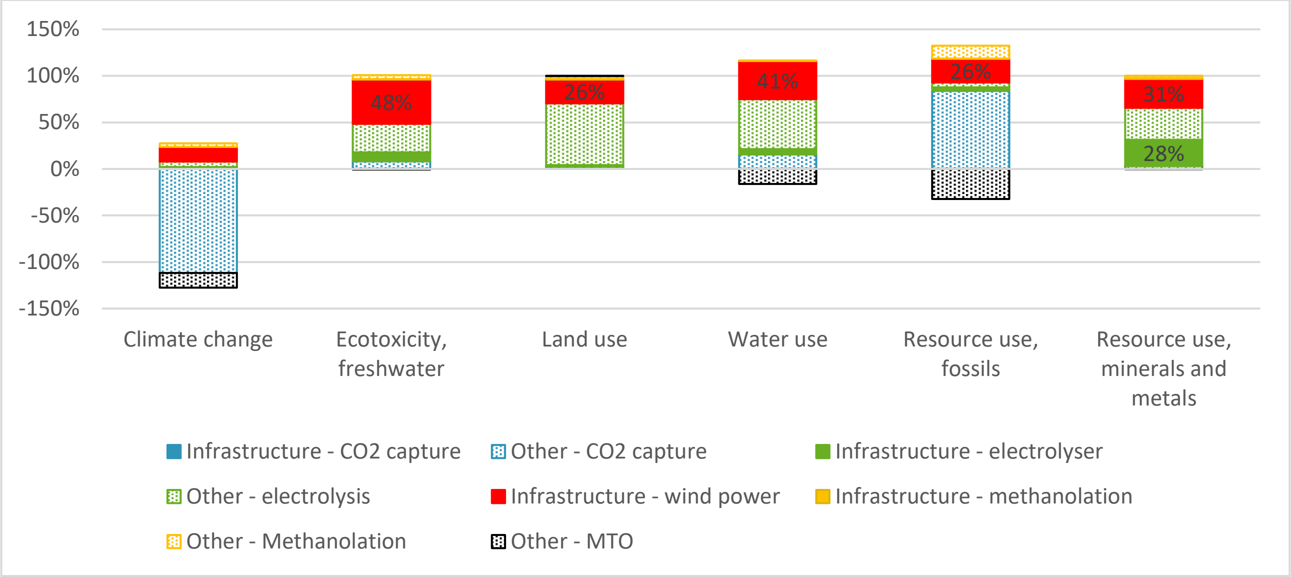
5.4 Influence of electricity



The source of electricity for electrolysis has a major impact on the results. 3 sources are studied: grid electricity, solar electricity and onshore wind electricity.

The majority of the impacts of wind and solar power are linked to the infrastructure (in particular the copper and aluminium used). Solar panels have a greater overall impact than wind turbines.

5.5 Infrastructure contribution



Below, in relation to the graph, the relative contribution of infrastructure to the total life cycle of e-fuels:

- The infrastructures for methanolation and CO_2 capture are negligible;
- Wind turbines are the infrastructure that generates the most impacts (between 26% and 48% excluding climate change);
- The electrolyser infrastructure also has a significant impact, particularly on the use of mineral resources (28%) because of the copper used.