Energy from different carriers emission factor evaluation

Supplementary information

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Index

1 Introduction

This document serves a double purpose:

- to provide sufficient information in order to allow replication for LCA practitioners,
- to provide detailed information and context to allow understanding of the calculation process to stakeholders without in-depth environmental knowledge.

The document reports emission factors (EFs) and EcoPoints (Eps) calculation for the following fuels:

- Diesel
- HVO
- Hydrogen (cryogenic storage)
- Hydrogen (300 bars compression)
- Methanol form Carbon Capture
- Urea

The reports also lists the emission factors, in terms of Global Warming Potential and EcoPoints, for the main substances involved in fuel production in chapter 4.1 “Direct Emission Factors”.

The software used for the calculation is **SimaPro**, data are sourced from the **Ecoinvent v. 3.9.1** database.

The **methods** used for the calculation are ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H and ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A.

2 The calculation method: ReCiPe 2016

ReCiPe 2016 Hierarchist (H) is a widely used life cycle impact assessment method that translates environmental inventory data into midpoint and endpoint impact scores based on consensus scientific modeling with a **100-year perspective**, enabling comprehensive and balanced evaluation of environmental impacts. Offering both midpoint and endpoint indicators, the method allows users to choose between a detailed analysis (midpoints) or a more simplified, overarching view of environmental impacts (endpoints). It targets LCA practitioners, researchers, policymakers, industry professionals, and consultants who need a versatile and reliable tool for environmental impact assessment. The ReCiPe 2016 midpoint method, Hierarchist version, is the default ReCiPe midpoint method.

The ReCiPe 2016 Hierarchist (H) method translates Life Cycle Inventory (LCI) data — emissions and resource extractions — into quantified environmental impacts through a sequence of well-defined steps, and can ultimately produce a single aggregated score called ecopoints.

2.1 Characterization (Midpoint Level)

Each inventory flow (e.g., kg of CO_2 emitted) is multiplied by a characterization factor that expresses its relative contribution to a specific environmental impact category (e.g., climate change, acidification). This converts diverse substances into a common reference unit per category (e.g., kg CO_2-equivalents for climate change) and results in 18 midpoint impact indicators. The Hierarchist perspective uses a 100-year time horizon reflecting consensus scientific views. The Midpoint impact categories are the following:

- Global warming [kg CO_2 eq]
- Stratospheric ozone depletion [kg CFC11 eq]
- Ionizing radiation [kBq Co-60 eq]
- Ozone formation [kg NO_x eq]
- Fine particulate matter formation [kg PM2.5 eq]
- Terrestrial acidification [kg SO_2 eq]
- Freshwater eutrophication [kg P eq]
- Marine eutrophication [kg N eq]
- Terrestrial ecotoxicity [kg 1,4-DCB]
- Freshwater ecotoxicity [kg 1,4-DCB]
- Marine ecotoxicity [kg 1,4-DCB]
- Human carcinogenic toxicity [kg 1,4-DCB]
- Human non-carcinogenic toxicity [kg 1,4-DCB]
- Land use [m2a crop eq]
- Mineral resource scarcity [kg Cu eq]
- Fossil resource scarcity [kg oil eq]
- Water consumption [m^3]

The impact on each of the Midpoint impact categories is evaluated through an LCA approach considering all the analysed processes related to the product, good or process.

2.2 Damage Assessment (From Midpoint to Endpoint Level)

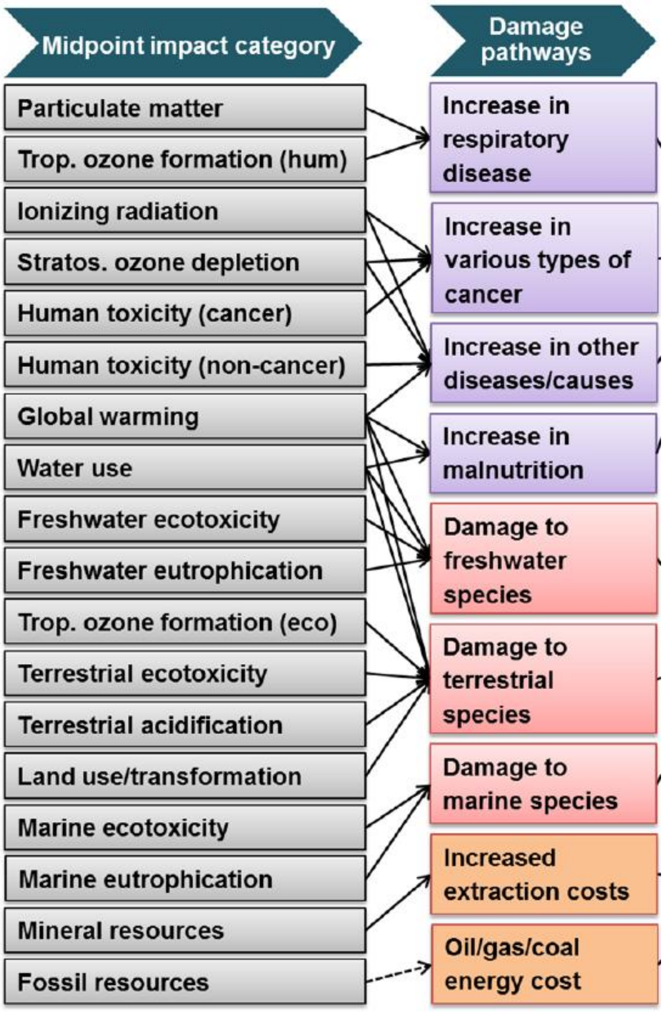
Midpoint indicators are further translated into damage on three areas of protection (endpoints):

- Human health (expressed in DALYs—disability-adjusted life years)
- Ecosystems (expressed in species lost over area and time)
- Resources (expressed in extra costs of future resource extraction)

Each Midpoint impact category is assigned one or more Damage pathways according to the damage that this category can generate. The Damage pathways are the following:

- Increase in respiratory disease;
- Increase in various types of cancer
- Increase in other disease/causes;
- Increase in malnutrition;
- Damage to freshwater species;
- Damage to terrestrial species;
- Damage to marine species
- Increased extraction costs
- Oil/gas/coal energy cost
-

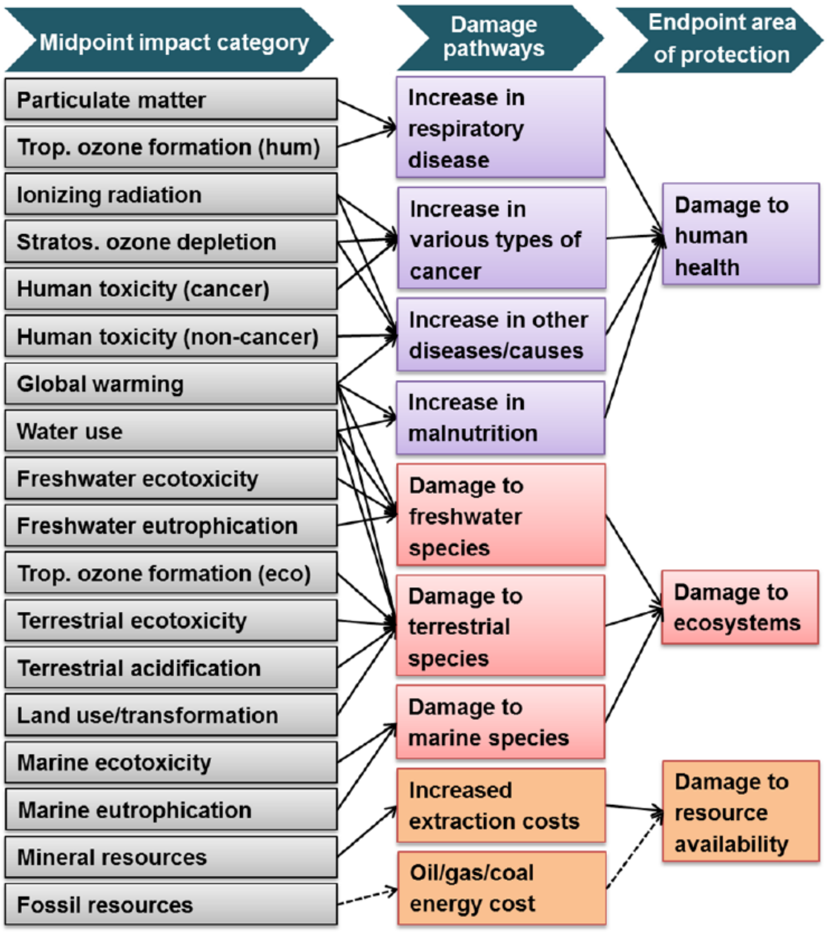
For example, the generation of particulate matter has negative effects that result in an increase in respiratory disease, while the use of water results in increased malnutrition, damage to freshwater species and damage to terrestrial species.
Below is a descriptive diagram of all the relationships between Midpoint impact categories and Damage Pathways.



Then the nine Damage pathways are merged into three Endpoints area of protection based on which natural element suffers the damage:

- Damage to human health;
- Damage to ecosystems;
- Damage to resource availability.

The relationship between Midpoint impact categories, Damage pathways and Endpoint area of protection is expressed in the following diagram.



Each Endpoint area of protection has its own unit of measurement, namely:

- Damage to human health: disability adjusted loss of life years (DALY), expressed in years;
- Damage to ecosystems: time integrated species loss, expressed in species per year;
- Damage to resource availability: surplus cost, expressed in 2013 US dollars.

Through appropriate emission factors (reported in appendix A), the impact of each Midpoint impact category is transformed into impact reported to the appropriate Endpoint area of protection.

This step aggregates and simplifies environmental mechanisms but introduces additional uncertainty.

2.3 Normalization

The damage or midpoint scores are divided by global reference values (normalization factors) representing the total environmental burden in the year 2010, creating dimensionless values.

This contextualizes the results, showing the relative significance of impacts compared to global impacts.

Normalization in ReCiPe 2016 H method places environmental impacts into context by expressing them relative to a reference total global environmental burden within a specific year (2010). This burden typically reflects the aggregated, worldwide emissions or resource uses for each impact category. Crucially, the normalization factors account for the total world population to provide an impact per person perspective. This means the total global burden is divided by the global population at that reference year, making normalization values interpretable as an average impact per person per year. Thus, when applying normalization factors, the impact score of a product or activity is divided by this normalized value (impact per person × global population), resulting in a dimensionless number that shows the relative magnitude of that impact compared to the global average per capita. This approach enables clearer communication and prioritization of environmental issues on a global human scale. The ReCiPe 2016 normalization spreadsheet reports normalized scores as impacts per person, reflecting individual contributions to global environmental burdens at the 2010 population level, derived from global emission inventories and population statistics. The key points are:

- Normalization factors represent *total global environmental impact* for year 2010 divided by *world population* in 2010.
- Results are expressed as *impact per person* per year, enabling comparisons across impact categories and regions.
- This approach contextualizes the environmental relevance of product impacts relative to global averages.

2.4 Weighting

Normalized results are multiplied by weighting factors that represent the relative importance of each impact category based on societal or expert preferences, integrating across categories

2.5 Aggregation into Ecopoints (Single Score)

Weighted scores for endpoints are summed to yield a single ecopoint score, expressing the overall environmental impact of the studied system or product as a single value. This score facilitates easier comparison and communication but carries cumulative uncertainties from all previous steps, and is intended to simplifiy decision making because it is evident whether a product's environmental impact is greater, lesser, or similar to that of other items.

After calculating the total impact on the three Endpoint areas of protection, a process of normalisation of the impacts obtained is carried out according to specific factors, which are shown in the following table.

Endpoint area of protection	Normalizing factor
Damage to human health	41.7
Damage to ecosystems	676
Damage to resource availability	3.57E-5

When the impacts are normalised according to the above mentioned factors, they are further multiplied by weight factors, which are shown in the following table.

Endpoint area of protection	Weighting factor
Damage to human health	400
Damage to ecosystems	400
Damage to resource availability	200

Once the weighing process has been carried out, the environmental impacts for the three Endpoint areas of protection are expressed in Ecopoints: therefore, the sum of the Ecopoints obtained for each endpoint area of protection is the overall score expressed in Ecopoint associated with this process.

The ReCiPe ecopoints reflect aggregated potential environmental damages across various impact categories and areas of protection, based on internationally harmonized models and global normalization references, particularly aligned with the 2010 global scale.

Ecopoints in ReCiPe 2016 are method-specific and should NOT be confused with "UBP Ecopoints" from the Swiss Ecological Scarcity method, which use a different methodology, unit definitions, and weighting principles. Although both use the term "ecopoints," their numerical values and interpretations are not interchangeable.

3 Environmental impacts

GWP and Ecopoints are the environmental metrics selected for the evaluation of the environmental performances.

In the journey toward sustainable development, one of the key priorities is to measure and minimize the environmental impact of various products and processes. Two crucial concepts that guide this measurement are the Global Warming Potential (GWP) and Ecopoints.

3.1 Global Warming Potential (GWP)

The Global Warming Potential, or GWP, is a metric used to compare the impact of various greenhouse gases on global warming. Not all greenhouse gases contribute equally to the greenhouse effect; some have a much higher heat-trapping capability than others. GWP measures this effect over a specific period, usually 100 years, and assigns each gas a value relative to carbon dioxide (CO_2), the baseline gas with a GWP value equal to 1.
As an example, methane (CH_4) has a GWP of about 25, meaning it is 25 times more effective at trapping heat than CO_2 over the same timeframe while nitrous oxide (N_2O) has a GWP of around 298, indicating an even greater effect on global warming. The GWP unit of measurement is then set in relation to the carbon dioxide value, and it is expressed in terms of mass of CO_2 equivalent.
The GWP values help policymakers, scientists, and companies evaluate and compare the impact of different gases, especially when deciding on targets for emissions reduction. In practical terms, GWP provides insight into how much more potent one gas is than another in contributing to climate change. Consequently, products and processes that release gases with high GWP values are seen as having a higher impact on global warming, guiding choices in product design, energy production, and industry regulations to minimize emissions.

GWP, being a midpoint impact category, is evaluated through the ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H method.

3.2 Ecopoints

Ecopoints are a distinct but complementary tool used in environmental impact assessment. While GWP focuses specifically on greenhouse gases and their role in global warming, ecopoints provide a more comprehensive measure of a product or process's overall environmental impact. Developed as part of life cycle assessment (LCA) frameworks, ecopoints evaluate various environmental effects, from resource depletion and pollution to waste generation and water consumption.

The ecopoints system assigns numerical values to these impacts, summing them into a single score that represents the total environmental burden. Higher ecopoints indicate a greater negative impact on the environment, and lower ecopoints suggest a more sustainable outcome. This measure allows manufacturers, consumers, and regulators to compare products or services from an environmental standpoint. The detailed evaluation process is explained in chapter 2.

EcoPoints, being referred to endpoint level, are evaluated through the ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A method.

Regarding the statement “100 Ecopoints = 1 EU citizen’s impact per year”:

This statement is **not correct** and should be avoided.

The **Ecopoints in ReCiPe 2016** represent **aggregated environmental impacts across multiple categories and damage areas** (human health, ecosystems, resources) using internationally harmonized life cycle impact assessment models and normalization factors based on a **global 2010 reference scale**.

It is important to note that:

ReCiPe Ecopoints are method-specific values expressed in a unit that aggregates various environmental damages weighted by damage factors and normalized to global-scale data. They should not be confused with “UBP Ecopoints” from the Swiss Ecological Scarcity method (UBA 2006), which employs a different methodology, unit definitions, and weighting approach. Although both use the term “Ecopoints,” the two methods have different numerical scales and interpretations, and their values are not interchangeable.

Therefore, **there is no simple direct equivalence** such as “100 Ecopoints equals the average environmental impact of one EU citizen per year.” The ReCiPe normalization reference is global, not regional, and the Ecopoint value represents a relative environmental burden normalized to global averages, **not an absolute per capita regional impact.**

4 Results obtained

The results obtained are presented first (in tables) and comments related to the reference processes are reported thereafter in every subchapter.

4.1 Direct emission factors

Document: Direct emission factors evaluation v.14-10-2024

			FU	Ecoinvent 3.9.1 (January 2023)	
				Ecopoint [Pt]	GWP [$kgCO_2eq$]
OUTPUT (DIRECT EMISSIONS)	AIRBORNE EMISSIONS	Ammonia	1 kg	2.63	0
		Carbon dioxide, fossil	1 kg	0.016	1
		Carbon monoxide, fossil	1 kg	0.00	0
		Heat, waste	1 MJ	0.00	0
		Hydrocarbons, aliphatic, alkanes, cyclic	1 kg	0.00775	0
		Hydrocarbons, aromatic	1 kg	0.0241	0
		Methane, fossil	1 kg	0.584	36
		Nitrogen oxides	1 kg	1.22	0
		NMVOC, non-methane volatile organic compounds, unspecified origin	1 kg	0.0128	0
		PAH, polycyclic aromatic hydrocarbons	1 kg	1.89	0
		Particulates, < 10 um	1 kg	0.00	0
		Particulates, < 2.5 um	1 kg	10.5	0
		Sulfur oxides	1 kg	3.09	0
	WATERBORNE EMISSIONS	Hydrocarbons, unspecified	1 kg	0.00	0
		Nitrogen oxides	1 kg	0.0000414	0

The above table presents the environmental impact of various direct emissions to air and water, using data from Ecoinvent 3.9.1 and evaluated through the ReCiPe 2016 (H) method in SimaPro. The focus is on two key metrics: the Global Warming Potential (GWP) expressed in kg CO_2-equivalent, and the aggregated environmental impact in Ecopoints (Pt). While GWP reflects the climate change contribution of greenhouse gases (GHGs) over a 100-year time horizon, Ecopoints integrate a broader set of impacts across human health, ecosystems, and resource availability.

Starting with the airborne emissions, it is immediately apparent that some substances, such as fossil methane, show a high GWP value (36 kg CO_2eq per kg emitted) due to their high radiative forcing capacity. Methane is significantly more relevant than carbon dioxide in trapping heat in the atmosphere over the 100-year perspective used by ReCiPe; thus, even in small quantities, its global warming impact is substantial. However, its corresponding Ecopoint score is relatively modest (0.584 Pt). This discrepancy arises because Ecopoints are a composite endpoint measure: they consider not only climate change, but also additional pathways such as toxicity, particulate formation, and acidification. Therefore, while methane contributes strongly to climate change, it does not significantly affect other damage categories.

Carbon dioxide, by definition, has a GWP of 1 per kg. Its low Ecopoint score (0.0162 Pt) reflects the fact that its environmental burden is limited primarily to global warming. It does not pose significant risks in terms of toxicity or ecotoxicity, nor does it directly impact human health through respiratory damage. Hence, its overall contribution to the endpoint damage categories used in ReCiPe is relatively small compared to other emissions.

On the other hand, substances like fine particulate matter (PM2.5), sulfur oxides (SO_x), ammonia, and nitrogen oxides have zero or negligible GWP values—because they are not greenhouse gases and do not trap infrared radiation—but their Ecopoint scores are among the highest. For instance, PM2.5 has an Ecopoint score of 10.5 Pt per kg, which reflects its severe health effects, particularly through increased incidence of cardiovascular and respiratory diseases. This impact is captured in ReCiPe under the human health damage category, expressed in DALYs (disability-adjusted life years). Sulfur oxides and ammonia also exhibit high Ecopoint values (3.09 Pt and 2.63 Pt per kg, respectively) due to their contribution to acidification and particulate formation, leading to ecosystem damage and human health degradation.

Some substances such as carbon monoxide and heat (waste) show zero values in both GWP and Ecopoints. For carbon monoxide, this is because—despite its toxicity—it is relatively short-lived in the atmosphere and does not directly contribute to long-term global warming or significant endpoint damages as defined by ReCiPe. The zero Ecopoint value does not necessarily mean there is no effect, but rather that its potential impacts fall outside the scope or thresholds of significance used in this methodology. Similarly, waste heat is considered an energy flow rather than a contaminant, and under the ReCiPe 2016 modeling framework, it is not associated with midpoint or endpoint damage pathways.

In the case of waterborne emissions, the table shows very low or zero values for both GWP and Ecopoints. This is consistent with the fact that the substances listed (unspecified hydrocarbons and nitrogen oxides in water) are either poorly characterized in terms of their impact through aquatic pathways in ReCiPe, or their contributions are minimal relative to the normalization factors. It's important to note that ReCiPe, like any impact assessment method, uses global averages and model-based thresholds; emissions that fall below certain impact thresholds or that lack comprehensive characterization factors may register as zero in the final results.

4.2 Diesel upstream emission factor

Document: Diesel emission factors evaluation v.14-10-2024

	$kgCO_2eq/kg$	Pt/kg
Diesel upstream	1,03	0.035

For the upstream phase, the Ecoinvent 3.9.1 dataset "*Diesel, low-sulfur {Europe without Switzerland}| diesel production, low-sulfur, petroleum refinery operation | Cut-off, U*" was used, covering all steps from crude oil extraction to diesel production.

The dataset used represents the life cycle inventory (LCI) of diesel fuel production at an average European petroleum refinery (excluding Switzerland), based on the ifeu refinery modeling tool. The tool simulates complex refinery operations, incorporating European Best Available Techniques (BREF) data, Eurostat statistics, confidential industrial data, and literature. It reflects average European refinery conditions: API gravity of 35, sulfur content of 1.03%, and a mix of refinery complexities (62% type II, 29% type III, 9% type IV). The dataset includes all processes from crude oil input to final diesel output. Additionally, real-world insights from a large yacht fuel supplier confirm that most yachts (80%) use EN590-compliant diesel (10ppm sulfur, FAME-free)—essentially automotive diesel—while the remaining 20% use LSMGO (Marine Gasoil with 0.1% sulfur).

The software gives as output the GWP and EcoPoint value to produce 1 kg of Low Sulfur Diesel running respectively ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H and ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A methods.

The Diesel Lower Heating Value considered is equal to 42,8 MJ/kg.

	$kgCO_2eq/kg$	Pt/kg
Diesel production	1,01	0.034

In table below, GWP and EcoPoint values for 100 km transport is reported running respectively ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H and ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A methods. *"Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U*" was considered.

	$kgCO_2eq/kg$	Pt/kg
Diesel transportation	0.02	0.001

The overall Upstream impact is evaluated by summing the impact related to the diesel production and transportation.

4.3 Urea

	$kgCO_2eq/kg$	Pt/kg
Urea upstream	1.44	0.049

For Upstream phase, "*Urea {RER}| urea production | Cut-off, U*" (Ecoinvent v. 3.9.1) was used for the calculation.

This dataset includes the entire production chain of urea within the European region, from the supply of raw materials (including ammonia and carbon dioxide) to the final urea product, excluding any downstream use or emissions.

The software gives us as output the GWP and EcoPoint value to produce 1 kg of Urea running respectively ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H and ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A methods.
The Diesel Lower Heating Value considered is equal to 42,8 MJ/kg.

	$kgCO_2eq/kg$	Pt/kg
Urea production	1.42	0.0048

In table below, GWP and EcoPoint values for 100 km transport is reported running respectively ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H and ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A methods. *"Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U"* was considered.

	$kgCO_2eq/kg$	Pt/kg
Urea transportation	0.02	0.001

The overall Upstream impact is evaluated by summing the impact related to the urea production and transportation.

4.4 HVO upstream emission factor

Document: HVO production impacts assessment v.05-10-2023

Environmental Indicator	Unit	Transport to the treatment plant	Pre-treament process	Production process	TOTAL
Global warming potential (GWP)	$kgCO_2eq$ /ton	46.72	92.05	524.69	**663.46**
Ecopoints	Pt/ton	1.52	2.83	11.84	**16.20**

The final impacts reported in the table above are related to the production process of **one ton of HVO.**

The following table reports the values for **one kg of HVO**:

Environmental Indicator	Unit	Transport to the treatment plant	Pre-treament process	Production process	TOTAL
Global warming potential (GWP)	$kgCO_2eq$ /kg_{HVO}	0.047	0.093	0.525	**0.663**
Ecopoints	Pt/kg_{HVO}	0.002	0.003	0.012	**0.016**

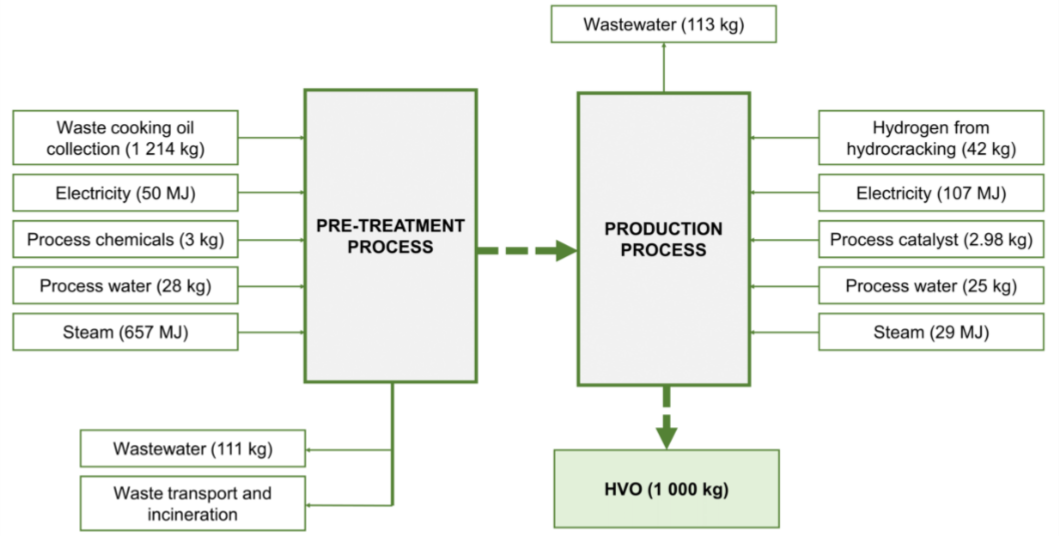
The obtained values show a reduction of around 35% with respect to the diesel production in terms of GWP.

Hydrogenated vegetable oil (HVO) has emerged as a promising and environmentally-friendly alternative fuel source in recent years. This renewable diesel is derived from various vegetable oils and fats, making it a sustainable choice for reducing the carbon footprint associated with transportation and energy production.
One of the key advantages of HVO fuel is its compatibility with existing diesel engines and infrastructure. It can be used as a drop-in replacement for conventional diesel, requiring no engine modifications or changes to fuelling stations. This ease of adoption makes it a practical choice for transitioning to cleaner energy sources while minimizing disruptions.
HVO also boasts several environmental benefits. It is sulfur-free, which means it produces fewer harmful emissions like sulfur dioxide (SO_2) and particulate matter when burned. Additionally, HVO exhibits a high cetane number, which enhances combustion efficiency and reduces engine noise, making it an attractive option for both commercial and consumer vehicles.
Furthermore, HVO's production process typically involves hydrogenation and hydrocracking of feedstocks such as vegetable oils, waste cooking oil, and animal fats. This process not only produces a cleaner-burning fuel but also helps recycle and repurpose materials that might otherwise go to waste.

In the context of climate change hydrogenated vegetable oil fuel use gaining a role in mitigating these issues. Its renewable nature, compatibility, and environmental benefits position it as a significant contributor to a more sustainable and greener future in the transportation and energy sectors.
The environmental impacts of producing HVO from waste cooking oil using the Life Cycle Assessment (LCA) approach are evaluated in this paper. During the analysis, all hypothesis, assumptions and limits will be described. The software used for the analysis is SimaPro 9.5 and the database is Ecoinvent 3.9 (ecoinvent.org).

4.4.1 System boundaries

The boundaries of the analysed system begin with the collection of waste oil and end at the finished product, as shown in the following image.



The quantities shown in the previous image refer to the production of **one ton** of produced HVO.
Since the raw material is a material from recycling it is not necessary to attribute to the production of HVO the impacts of its previous life (i.e., cultivation, harvesting, production of cooking oil etc...). This hypothesis makes sense if waste cooking oil is used as raw material: for the specific case of production of HVO from not exhausted oils it is necessary to include also all the agriculture phase.

4.4.2 Life Cycle Inventory (LCI)

All data available in the literature relevant to the production of HVO from waste cooking oil are reported in this chapter. All data are taken from the only available bibliographical reference (S. Nikander, 2008). It is not easy to find such detailed information about industrial production processes: the cited study is conducted in collaboration with Neste, the world

leader in biofuel production. The results obtained will then be compared with other studies to guarantee the accuracy of the data used.
The reported quantities refer to the functional unit defined by **1 ton of HVO produced**.

4.4.3 Pre-treatment process

The following table shows the data used in the pre-treatment process modelling for the production of one ton of HVO.

INPUT		
Data	**Value**	**Process**
WCO inbound transport	243 t*km	*Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5*
Electricity	50 MJ	*Electricity, low voltage, {Europe without Switzerland}| market group for electricity, low voltage | Cut-off, U*
Process chemicals	3 kg	*Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U*
Process water	28 kg	*Tap water {Europe without Switzerland}| market for tap water | Cut-off, U*
Steam	657 MJ	*Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | Cut-off, U*
OUTPUT		
Data	**Value**	**Process**
Dried solid waste	13 kg	*European average incineration treatment*
Dried solid waste transport	2.6 t*km	*Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5*
Wastewater	111 kg	*Waste water*

Unlike the study to which reference is made, which provides for the dedicated production of vegetable oils for the production of HVO, has taken an average collection distance of waste oils of 200 km. It was also necessary to model the transport of waste by incineration, again assuming a distance of 200 km. For both transports it was assumed that the distance was covered by a lorry of size 16-32 metric ton of environmental class euro 5.
Moreover, it has been assumed the use of electric energy with an electricity mix of representative of the European average.

4.4.4 Production process

The following table shows the data used in the production process modelling for the production of one ton of HVO.

INPUT		
Data	**Value**	**Process**
Hydrogen	42 kg	*Hydrogen, gaseous {RER}| hydrogen production, steam reforming, | Cut-of, U*
Electricity	107 MJ	*Electricity, low voltage, {Europe without Switzerland}| market group for electricity, low voltage | Cut-off, U*
Process chemicals	2.98 kg	*Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U*
Process water	25 kg	*Tap water {Europe without Switzerland}| market for tap water | Cut-off, U*
Steam	29 MJ	*Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | Cut-off, U*
OUTPUT		
Data	**Value**	**Process**
Wastewater	113 kg	*Waste water*

The hydrogen used in this phase has been considered produced by steam reforming as, to date, this is the most common practice.
Also in this case, it has been assumed the use of electric energy with an electricity mix representative of the European average.

4.4.5 Life Cycle Impact Assessment (LCIA)

The results of the Life Cycle Assessment are presented according to two environmental indicators: the GWP (Global Warming Potential) of a substance, that is the ratio between the contribution to the absorption of hot radiation that is provided by the instantaneous release of 1 kg of this substance and that provided by the emission of 1 kg of CO_2 (assessed for a period of 100 years during which the gases remain in the atmosphere), and the Ecopoint, that is a unit of measurement for a unit, product, or material's environmental impact, derived as a sum in this study from the combined results of a life cycle evaluation against the 18 impact categories combined utilizing damage factors and aggregated into three endpoint categories (Human health, Ecosystems, and Resource scarcity).

4.5 Methanol from CC upstream emission factor

Document: Methanol from CC production impacts assessment v.31-10-2023

Environmental Indicator	Unit	Production process	TOTAL
Global warming potential (GWP)/ton	$kgCO_2eq$	944.3	**944.3**
Ecopoints/ton	Pt	26.2	**26.2**

The final impacts reported in the table above are related to the production process of one ton of Methanol from Carbon Capture. The following table reports the values for one kg of Methanol from Carbon Capture:

Environmental Indicator	Unit	Production process	TOTAL
Global warming potential (GWP)/kg	$kgCO_2eq$	0.94	**0.94**
Ecopoints/kg	Pt	0.02	**0.02**

Methanol production from carbon capture of industrial exhaust gases represents a promising solution for environmental sustainability and energy utilization. Due to the urgent need to reduce carbon emissions, innovative approaches to capture and utilize carbon dioxide are gaining significant attention. This emerging technology involves capturing CO_2 emissions from various industrial sources, preventing them from entering the atmosphere and contributing to climate change, and then converting this captured carbon into valuable methanol.

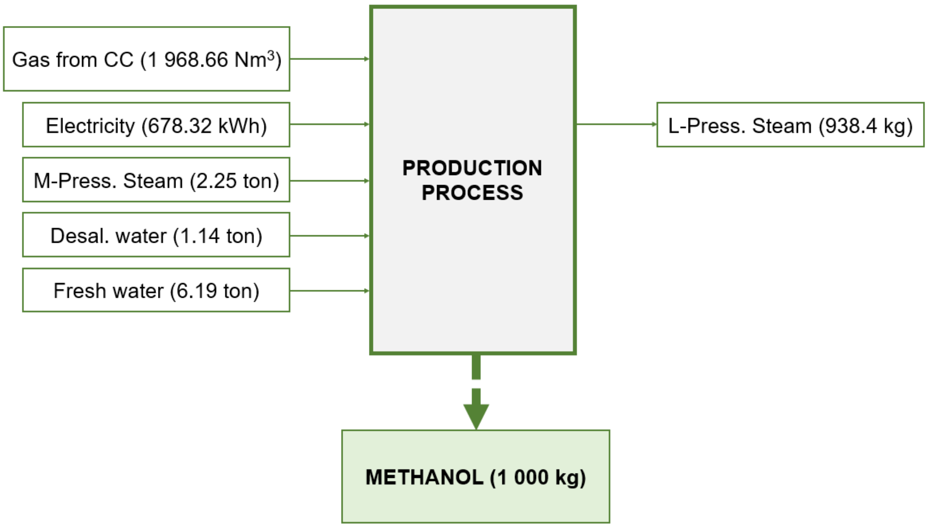
Green methanol and e-methanol are both renewable forms of methanol, but they differ in their production methods. E-methanol, also known as electro-methanol, is produced by reacting green hydrogen (derived from renewable electricity) with captured carbon dioxide. Green methanol, on the other hand, is a broader term encompassing both e-methanol and biomethanol, which is produced from biomass. Both are considered sustainable alternatives to traditional fossil fuel-based methanol due to their lower carbon footprint.

As such the process modelled in the reference study can not be classified as “green methanol” because it does not involve the use of solely renewable energy, nor as e-methanol for the same reason. Based on the classification discussed in the literature, methanol produced from captured carbon in coke oven gas using non-renewable energy sources should be more accurately referred to as "blue methanol", as it relies on carbon capture and utilization (CCU) technologies applied to fossil-based industrial emissions, without fully integrating renewable energy into the production process

The environmental impacts of producing methanol from carbon capture of industrial exhaust gases using the Life Cycle Assessment (LCA) approach are evaluated in this paper. During the analysis, all hypothesis, assumptions and limits will be described. The software used for the analysis is SimaPro 9.5 and the database is Ecoinvent 3.9 (ecoinvent.org).

4.5.1 System boundaries

The purpose of the study is to analyse the environmental impacts related to the production of methanol from carbon capture of industrial exhaust gases: this means that the boundaries of the analysed system begin with the capture of industrial exhaust gases and end at the finished product, as shown in the following image.



The quantities shown in the previous image refer to the production of one ton of methanol produced from carbon capture of industrial exhaust gases.

Since the raw material (gas from caron capture) is a material from reuse it is not necessary to attribute to the production of methanol its production impacts.

4.5.2 Life Cycle Inventory (LCI)

All data are taken from the study conducted by J. Li et al. in 2018. It is not easy to find such detailed information about industrial production processes: the cited study refers to the production of methanol from coke oven gas: this type of industry is considered as a reference in this study.

The results obtained will then be compared with other studies to guarantee the accuracy of the data used.

The reported quantities refer to the functional unit defined by **1 ton of methanol produced**.

Production process

The following table shows the data used in the pre-treatment process modelling for the production of one ton of methanol from carbon capture.

INPUT		
Data	**Value**	**Process**
Electricity	678.32 kWh	*Electricity, low voltage, {Europe without Switzerland}| market group for electricity, low voltage | Cut-off, U*
Medium pressure steam	2.25 ton	*Steam, in chemical industry {RER}| steam production, in chemical industry | Cut-off, U*
Desalinated water	1.14 ton	*Tap water {RER}| market for tap water | Cut-off, U*
Fresh water	6.19 ton	*Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U*
OUTPUT		
Data	**Value**	**Process**
Low pressure steam	938.35 kg	*Water*

Unlike the study to which reference is made, the exhausted gas as output are excluded since they are captured and used for syngas production.

Moreover, it has been assumed the use of electric energy with an electricity mix of representative of the European average.

4.5.3 Life Cycle Impact Assessment (LCIA)

The results of the Life Cycle Assessment are presented according to two environmental indicators: the GWP (Global Warming Potential) of a substance, that is the ratio between the contribution to the absorption of hot radiation that is provided by the instantaneous release of 1 kg of this substance and that provided by the emission of 1 kg of CO_2 (assessed for a period of 100 years during which the gases remain in the atmosphere), and the Ecopoint, that is a unit of measurement for a unit, product, or material's environmental impact, derived as a sum in this study from the combined results of a life cycle evaluation against the 18 impact categories combined utilizing damage factors and aggregated into three endpoint categories (Human health, Ecosystems, and Resource scarcity).

4.6 Hydrogen from electrolysis (300 bar compression) upstream emission factor

Document: Hydrogen from hydrolysis (300 bar compression) production impacts assessment v.30-11-2023

GWP unit	Process	RER	PV	WIND
Global warming [$kgCO_2eq/Nm^3$]	Electrolysis	1.81	0.45	0.22
	Compression	0.06	0.01	0.006
	Total	**1.87**	**0.46**	**0.22**

GWP unit	Process	RER	PV	WIND
Global warming [$kgCO_2eq/kg$]	Electrolysis	20.1	4.96	2.40
	Compression	0.8	0.17	0.07
	Total	**20.9**	**5.13**	**2.47**

Ecopoints unit	Process	RER	PV	WIND
Global warming [Pt/Nm^3]	Electrolysis	64.0	24.1	14.1
	Compression	2.33	0.9	0.49
	Total	**66.3**	**25.0**	**14.6**

Ecopoints unit	Process	RER	PV	WIND
Global warming [Pt/kg]	Electrolysis	712	268	157
	Compression	25.9	9.53	5.41
	Total	**738.9**	**278**	**162**

Hydrogen, a versatile and clean energy carrier, has gained significant attention as a potential solution for addressing environmental challenges and transitioning towards sustainable energy systems. One of the key methods for hydrogen production is through hydrolysis, a process that involves splitting water molecules into hydrogen and oxygen using an external energy source. This environmentally friendly approach has garnered interest for its potential to harness renewable energy sources, such as solar or wind, to generate hydrogen.

As the world seeks to reduce its reliance on fossil fuels and mitigate climate change, the production and storage of hydrogen have become focal points of research and development.

The compression of hydrogen to 300 bar, is a key step in its storage and transportation, enhancing its energy density and facilitating efficient utilization across different industries.

Since the environmental impacts strongly relies on the electricity consumption, three different scenarios of electricity mix used are investigated:

1. RER: it is assumed to use the average European electricity mix;
2. PV: it is assumed to use 100% of electricity coming from photovoltaic power plants;
3. WIND: it is assumed to use 100% of electricity coming from wind power plants.

The environmental impacts of producing hydrogen from hydrolysis, and its storage through the 300 bar compression process, using the Life Cycle Assessment (LCA) approach are evaluated in this paper. During the analysis, all hypothesis, assumptions and limits will be described. The software used for the analysis is SimaPro 9.5 and the database is Ecoinvent 3.9 (ecoinvent.org).

4.6.1 System boundaries

The purpose of the study is to analyse the environmental impacts related to the production of hydrogen from hydrolysis, and its storage through the compression to 300 bar. The picture below summarizes the system boundaries considered.

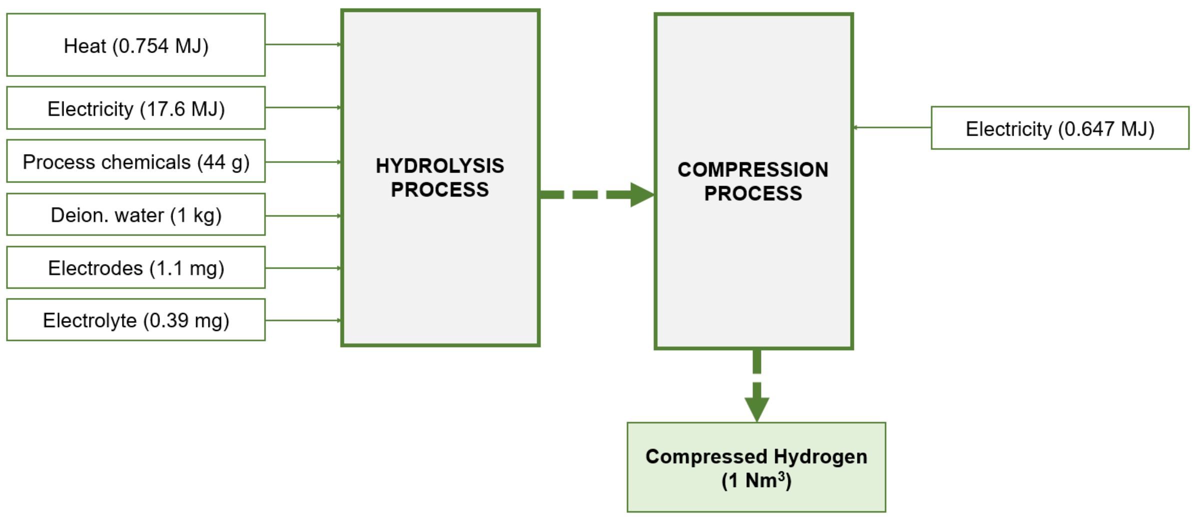
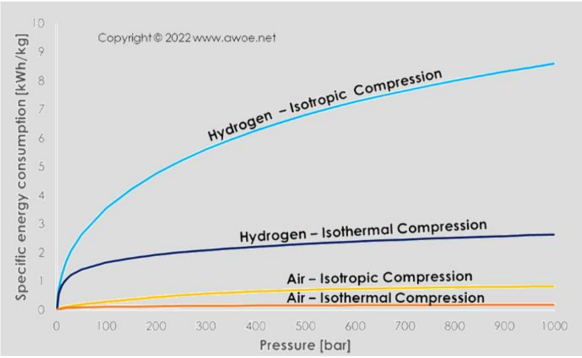


Figure - System boundaries

The quantities shown in the previous image refer to the production and transformation through the compression process of one normal cubic meter of hydrogen produced from hydrolysis.

4.6.2 Life Cycle Inventory (LCI)

All data referring to the hydrolysis process are taken from the study conducted by J. Dufour et al. in 2012, while data about energy consumption related to the compression to 300 bar are taken from awoe.net[1] a assuming an isothermal compression process.



Graph - Hydrogen compression energy consumptions

The results obtained will then be compared with other studies to guarantee the accuracy of the data used. The reported quantities refer to the functional unit defined by 1 cubic meter in normal conditions (20 °C, 1 atm) of hydrogen produced and stored.

The following table shows the data used in the hydrolysis and compression processes modelling for the production of one 1 cubic meter of hydrogen.

HYDROLYSIS		
Data	Value	Process
Electricity	1.76E+01 MJ	*RER*
		PV
		WIND
Heat, as natural gas	7.54E-01 MJ	*Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Cut-off, U*
Electrodes	1.10E-06 kg	*Electrode, negative, Ni {GLO}| market for electrode, negative, Ni | Cut-off, U*
Electrolyte consumption	3.90E-07 kg	*Electrolyte, KOH, LiOH additive {GLO}| market for electrolyte, KOH, LiOH additive | Cut-off, U*
Diaphragm and other materials	4.40E-04 kg	*Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U*
Deionised water	1 kg	*Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U*
300 BAR COMPRESSION PROCESS		
Data	Value	Process
Electricity	6.47E-01 MJ	*RER*
		PV
		WIND

Table – Production and compression process data

4.6.3 Life Cycle Impact Assessment (LCIA)

The results of the Life Cycle Assessment are presented according to two environmental indicators: the GWP (Global Warming Potential) of a substance, that is the ratio between the contribution to the absorption of hot radiation that is provided by the instantaneous release of 1 kg of this substance and that provided by the emission of 1 kg of CO_2 (assessed for a period of 100 years during which the gases remain in the atmosphere), and the Ecopoint, that is a unit of measurement for a unit, product, or material's environmental impact, derived as a sum in this study from the combined results of a life cycle evaluation against the 18 impact categories combined utilizing damage factors and aggregated into three endpoint categories (Human health, Ecosystems, and Resource scarcity).

4.7 Hydrogen from electrolysis (cryogenic storage) upstream emission factor

Document: Hydrogen from hydrolysis (cryogenic storage) production impacts assessment v.29-11-2023

GWP unit	Process	RER	PV	WIND
Global warming [kgCO_2eq/Nm^3]	Electrolysis	1.81	0.45	0.21
	Compression	0.45	0.04	0.05
	Total	**2.26**	**0.49**	**0.26**

GWP unit	Process	RER	PV	WIND
Global warming [kgCO_2eq/kg]	Electrolysis	20.1	4.96	2.40
	Compression	4.99	0.49	0.49
	Total	**2.51**	**5.45**	**2.89**

Hydrogen, a versatile and clean energy carrier, has gained significant attention as a potential solution for addressing environmental challenges and transitioning towards sustainable energy systems. One of the key methods for hydrogen production is through hydrolysis, a process that involves splitting water molecules into hydrogen and oxygen using an external energy source. This environmentally friendly approach has garnered interest for its potential to harness renewable energy sources, such as solar or wind, to generate hydrogen.

As the world seeks to reduce its reliance on fossil fuels and mitigate climate change, the production and storage of hydrogen have become focal points of research and development. Cryogenic storage, in particular, offers a promising solution for efficiently storing large quantities of hydrogen. This method involves cooling hydrogen to extremely low temperatures, typically below -253 degrees Celsius, transforming it into a liquid state and reducing its volume, making it more economically viable for long-term storage and transportation.

Since the environmental impacts strongly relies on the electricity consumption, three different scenarios of electricity mix used are investigated:

1. RER: it is assumed to use the average European electricity mix;
2. PV: it is assumed to use 100% of electricity coming from photovoltaic power plants;
3. WIND: it is assumed to use 100% of electricity coming from wind power plants.

The environmental impacts of producing hydrogen from hydrolysis, and its storage through the cryogenic process, using the Life Cycle Assessment (LCA) approach are evaluated in this paper. During the analysis, all hypothesis, assumptions and limits will be described. The software used for the analysis is SimaPro 9.5 and the database is Ecoinvent 3.9 (ecoinvent.org).

4.7.1 System boundaries

The purpose of the study is to analyse the environmental impacts related to the production of hydrogen from hydrolysis, and its storage through the cryogenic process. The picture below summarizes the system boundaries considered.

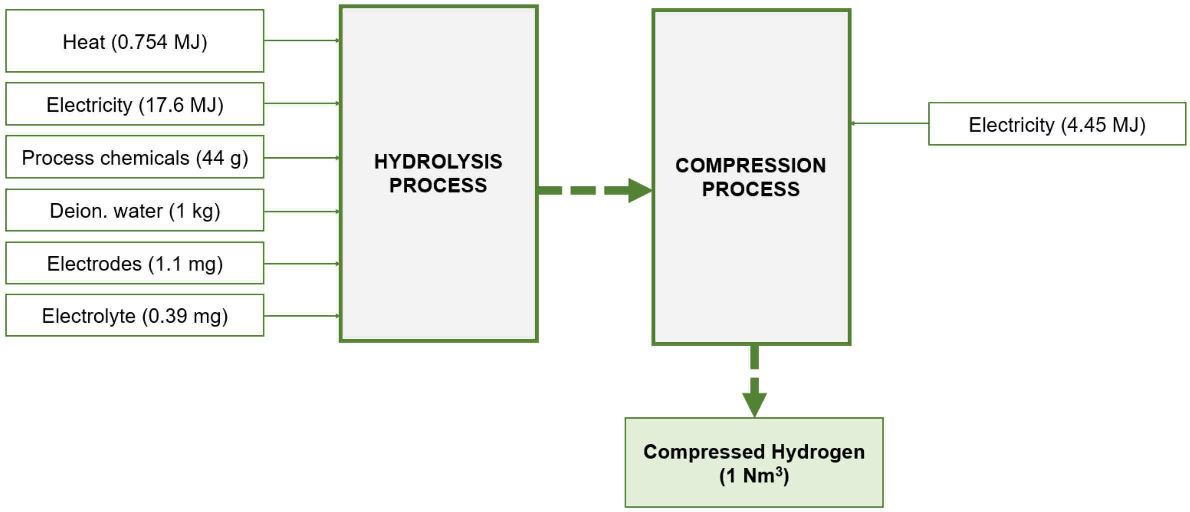


Figure - System boundaries

The quantities shown in the previous image refer to the production and transformation through the cryogenic process of one normal cubic meter of hydrogen produced from hydrolysis.

4.7.2 Life Cycle Inventory (LCI)

All data referring to the hydrolysis process are taken from the study conducted by J. Dufour et al. in 2012, while data about energy consumption related to the cryogenic transformation are taken from the study conducted by R. Folkson and S. Sapsford in 2022. The results obtained will then be compared with other studies to guarantee the accuracy of the data used.

The reported quantities refer to the functional unit defined by **1 cubic meter in normal conditions (20 °C, 1 atm) of hydrogen produced and stored**.

The following table shows the data used in the hydrolysis and cryogenic processes modelling for the production of one 1 cubic meter of hydrogen.

HYDROLYSIS		
Data	**Value**	**Process**
Electricity	1.76E+01 MJ	*RER*
		PV
		WIND
Heat, as natural gas	7.54E-01 MJ	*Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Cut-off, U*
Electrodes	1.10E-06 kg	*Electrode, negative, Ni {GLO}| market for electrode, negative, Ni | Cut-off, U*
Electrolyte consumption	3.90E-07 kg	*Electrolyte, KOH, LiOH additive {GLO}| market for electrolyte, KOH, LiOH additive | Cut-off, U*
Diaphragm and other materials	4.40E-04 kg	*Chemical, inorganic {GLO}| market for chemical, inorganic | Cut-off, U*
Deionised water	1 kg	*Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U*
CRYOGENIC PROCESS		
Data	**Value**	**Process**
Electricity	4.45 MJ	*RER*
		PV
		WIND

Table 1 – Production and cryogenic process data

4.7.3 Life Cycle Impact Assessment (LCIA)

The results of the Life Cycle Assessment are presented according to two environmental indicators: the GWP (Global Warming Potential) of a substance, that is the ratio between the contribution to the absorption of hot radiation that is provided by the instantaneous release of 1 kg of this substance and that provided by the emission of 1 kg of CO_2 (assessed for a period of 100 years during which the gases remain in the atmosphere), and the Ecopoint, that is a unit of measurement for a unit, product, or material's environmental impact, derived as a sum in this study from the combined results of a life cycle evaluation against the 18 impact categories combined utilizing damage factors and aggregated into three endpoint categories (Human health, Ecosystems, and Resource scarcity).

Appendix A

	Unit[1,2]	H
Human health		
climate change	yr/kg CO_2 to air	9.3E-07
ozone depletion	yr/kg CFC11 to air	5.3E-04
ionizing radiation	yr//kBq Co-60 to air	8.5E-09
fine particulate matter formation	yr/kg PM2.5 to air	6.3E-04
photochemical ozone formation	yr/kg NOx to air	9.1E-07
cancer toxicity	yr/kg 1,4-DCB to air	3.3E-06
non-cancer toxicity	yr/kg 1,4-DCB to air	6.7E-09
water use	yr/m^3 water	2.2E-06
Ecosystem quality: terrestrial		
climate change	species.yr/kg CO_2 to air	2.8E-09
photochemical ozone formation	species.yr/kg NO_x to air	1.3E-07
acidification	species.yr/kg SO_2 to air	2.1E-07
toxicity	species.yr/kg 1,4-DCB to industrial soil	5.4E-08
water use	species.yr/m^3 water consumed	1.4E-08
land use	species/m^2 annual crop land	8.9E-09
Ecosystem quality: fresh water		
climate change	species.yr/kg CO_2	7.7E-14
eutrophication	species.yr/kg P to fresh water	6.1E-07
toxicity	species.yr/kg 1,4-DCB to fresh water	7.0E-10
water use	species.yr/m^3 water consumed	6.0E-13
Ecosystem quality: marine		
toxicity	species.yr/kg 1,4-DCB	1.1E-10
eutrophication	species.yr/kg N to marine water	1.7E-09
Resource scarcity		
minerals	US_{2013} \$/kg Cu	0.23
fossils[3]	US_{2013} \$/kg crude oil	0.46
	US_{2013} \$/kg hard coal	0.03
	US_{2013} \$/Nm^3 natural gas	0.30

1 The unit for human health damage refers to the disability adjusted life years lo human population; 2 the units for ecosystem damage refer to the number of spe integrated over time; 3 fossil resource scarcity is the only midpoint category whi have a constant midpoint to endpoint factor.