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REDHY

Redox-Mediated economic, critical raw material free, low capex and highly efficient green hydrogen production technology

REDHY - Deliverable report

DELIVERABLE 7.1 – Preliminary LCA of REDHy system

Clean Hydrogen Partnership

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Author(s)	Davide Rovelli, Fabiana Forciniti	
Checked by	Davide Rovelli (IDN)	
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Public Summary

Deliverable 7.1 provides the Preliminary Life Cycle Assessment (LCA) of the REDHY system. The assessment adopts cradle-to-grave system boundaries to offer a comprehensive view of the potential environmental impacts throughout the entire lifecycle of the system. Primary data were collected by project partners, and multiple scenarios were analyzed where alternative options remain under consideration.

Additionally, cradle-to-gate results are benchmarked against literature references. Currently, REDHy impacts with respect to commercial water electrolysis technologies are higher due to unoptimized electricity consumption of manufacturing processes at lab scale and the early stage of development of the project. The components which result in higher contribution are the stack and the electrodes.

The report also outlines the study's limitations and identifies key areas for improvement to guide the next LCA iteration as the REDHY project progresses.

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Abbreviations & Definitions

Abbreviation	**Explanation**
AWE	Alkaline Water Electrolyser
AEMWE	Anionic Membrane Water Electrolyser
BoM	Bill of Material
BoP	Balance of Plant
BPP	Bipolar Plate
EoL	End of Life
HER	Hydrogen Evolution Reaction
LCIA	Life Cycle Impact Assessment
LCI	Life cycle Inventory
Ni	Nickel
OER	Oxygen Evolution Reaction
PEMWE	Proton Exchange Membrane Water Electrolyser
PP	Polypropylene
PSU	Polysulfone
SoA	State of the Art
SOEC	Solid Oxide Electrolysis Cell
SS	Stainless Steel
WP	Work Package

Item	**Definition**
Bill of Material	Presentation of the constituents in a product structure with the possibility to adopt the level of decomposition to actual need. [1]
Manufacturing	Processes and actions performed by an equipment supplier/manufacturer that are necessary to provide finished component(s), assembly(ies) and related documentation, that fulfill the requests of the user/purchaser and meet the standards of the supplier/manufacturer. Note to entry: Manufacturing begins when the supplier/manufacturer receives the order and is completed at the moment the component(s), assembly(ies) and related documentation are surrendered to a transportation provider.
Electrolyzer	Electrochemical device that converts water/steam and/or CO2 to hydrogen and oxygen by electrolysis reaction.
Electrode	Conductive part in electric contact with a medium of lower conductivity and intended to perform one or more of the functions of emitting charge carriers to or receiving charge carriers from that medium or to establish an electric field in that medium. [1]
Membrane	Material that provides separation between oxygen and hydrogen product gases while allowing ionic transport within the cell. [1]
Catalyst loading or catalyst load	Amount of catalyst incorporated in the electrochemical cell (EC) per unit active area, specified either per anode or cathode separately, or specified as combined anode and cathode loading. [1]
Electrolyte	Liquid or solid substance containing mobile ions which render it ionically conductive

	Note to entry: the electrolyte may be liquid, solid or a gel. [1]
Stack	Assembly of more than one electrolysis cell, mostly in a filter press arrangement and connected electrically either in parallel (monopolar assembly), in full series (bipolar assembly) or in series with a central anode and hydraulically in parallel Note to entry: An electrolysis stack consists of further components such as separators, cooling plates, manifolds and a supporting structure. The typical components of an electrolysis stack are: membrane or diaphragm, electrodes (anode and cathode), porous transport layers or liquid gas diffusion layer, bipolar plate (BPP) as a separator plate between two adjacent electrolysis cells, sometimes with additional flow fields for an easier fluid distribution, cell frames and/or gaskets and/or sealing, current distributor, end plates for mechanical compression, electrical terminals, remaining component of the stack such as tie bolts, etc. [1]
Piping	Any combination of connectors, couplings, tubes and/or hoses which allows fluid flow between components.[1]
Balance of Plant	Arrangement of all supporting and auxiliary components and devices needed for fluid, thermal and electrical management of the system and its safe and reliable operation whether locally or remotely. [1]
Bipolar Plate	Electrical conductive and gas-tight plate separating individual cells in a single cell or stack, acting as a reagent flow distributor and current distributor and providing mechanical support for the electrodes or membrane electrode assembly. [1]
End plate	Component located on either end of the electrolysis cell or stack to transmit the required compression to the stacked cells to allow proper electrical contact and to avoid fluid leaks. [1]
O-ring	Moulded elastomeric seal that has a round cross-section in the free state.[1]
Gasket	Component that prevents the exchange of fluids between two or more compartments of a device or the leakage of fluids from a device to the outside. [1]
Single (electrolysis) cell	Basic unit of an electrolysis device composed of three functional elements, namely a cathode, an electrolyte and an anode, which are capable of breaking up chemical compounds by means of applied electrical energy to produce reduced and oxidised compounds. [1]
Power consumption	Total power consumed by a component or system under specified conditions. [1]
Energy consumption	Power consumption over a certain time period. [1]
Lifetime	Period over which any of the item properties are required to be within defined limits

1. Introduction

The REDHy project tackles the limitations of contemporary electrolyser technologies by fundamentally reimagining water electrolysis, allowing it to surpass the drawbacks of state-of-the-art (SoA) electrolysers and become a pivotal technology in the hydrogen economy. The REDHy approach is highly adaptable, enduring, environmentally friendly, intrinsically secure, and cost-efficient, enabling the production of economically viable green hydrogen at considerably increased current densities compared to SoA electrolysers. Unlike SoA electrolysers, REDHy is entirely free of critical raw materials and doesn't require fluorinated membranes or ionomers, while maintaining the potential to fulfil a substantial portion of the Clean Hydrogen JU SRIA 2024 KPIs.

The aim of Task 7.1 is to perform a preliminary LCA both to evaluate and identify opportunities to improve the environmental behavior of the REDHy technology during the development process, by providing ex-ante ecodesign measures.

To this end, firstly, benchmarking of REDHy impacts within LCA results, taken from public literature (academic research papers, technical reports etc..) of other hydrogen production technologies has been carried out, with a special focus on electrolysis technologies.

Secondly, an inventory analysis from a life cycle perspective (LCI) has been developed, taking into account all stages in the value chain including upstream and downstream processes related to the use and end-of-life phases of the system. The analysis aims at quantifying all the incoming and outgoing material flows (e.g., extracted or emitted into the environment), as well as the energy flows along the novel technology. The comprehensive LCI has been developed by mainly using the information gathered from partners and results of previous WPs as well as reliable and available literature sources, industry-average life-cycle data from life cycle inventory databases. Potential REDHy development scenarios and evaluation of alternative materials or components have also been included in the assessment, depending on the partners' inputs.

In particular, UPV provided data on Redox mediators developed in WP2, CenMAT provided data on the membrane developed in WP3, CNRS and CNR provided data on the electrodes developed in WP4, the characteristics of the single cells will be provided by CENMAT and CNR and finally DLR provided the data about the stack and Balance of Plant components developed in WP6.

The impact assessment aim is to classify and evaluate the environmental impacts of the REDHy technology, in order to provide specific conclusions and recommendations based on the attained results through the set of indicators and impact categories selected under a LCA perspective. This will lead to outlining the most relevant bottlenecks in terms of environmental impacts and evaluating trade-offs between environmental impact categories, while providing preliminary eco-design measures main actors in the value chain to drive the project towards environmentally friendly decisions.

Sensitivity analyses have been performed for the most relevant consumption items (e.g. evaluation of different supply mixes for electricity consumed in the use phase).

This deliverable highlights the methodology and results of the preliminary Life Cycle Assessment (LCA) conducted within the REDHy project. It includes a Life Cycle Interpretation of the findings, highlighting the main limitations of the study and identifying areas for improvement.

Within the scope of Task 7.1, all objectives have been addressed. The identified criticalities and issues serve as a foundation for further investigation and will be examined in greater detail in Tasks 7.2 and 7.3, in alignment with the latest developments of the project.

2. Technological background

2.1 Hydrogen production through water electrolysis technologies

Electrolysis is the use of direct current to drive an otherwise non-spontaneous (endergonic) electrochemical reaction. Besides liquid water electrolysis for the production of hydrogen and oxygen, electrolysis has other applications most notably in chlor-alkali electrolysis to produce chlorine for use in chemical industry and hydrogen as by-product, photo electrolysis using directly solar energy to produce hydrogen and oxygen, carbon dioxide capture by electrolytic carbonate formation, waste water treatment (i.e. electro-chlorination), and molten (fused) salt electrolysis used in (hydro-)metallurgical industry to produce (recover) metals [1].

Regarding hydrogen production through water electrolysis, the Joint Research Centre (JRC) of the European Commission has classified and assessed the electrolyzers technologies as either low-temperature electrolyzers and high-temperature electrolyzers.

Low temperature water electrolysis refers to temperatures usually between 50 and 90°C. High temperature refers to temperatures between 500 °C and 1000 °C. [1] Alkaline water electrolyzers (AWE), proton exchange membrane (PEM) electrolyzers and anion exchange membrane (AEM) electrolyzers are classified as low temperature electrolyzers. In contrast, the solid oxide electrolyzer cell (SOEC) belongs to the category of high temperature electrolyzers [2] [1].

Furthermore, the water electrolysis technologies were classified according to their electrolyte, operating conditions, and ionic agents (OH^-, H^+ , and O^{2-}), as reported in figures below [2].

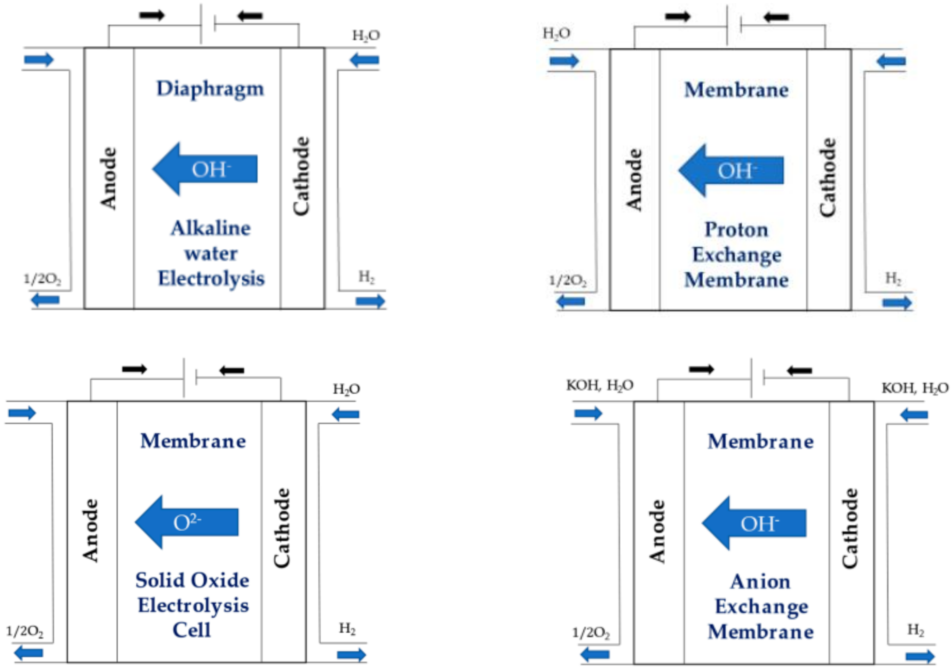


Figure 1. Water electrolysis reaction mechanism for different technologies

The technology readiness level (TRL) represents the technological maturity of technology readiness toward the market. Since 2014, the Technology Readiness Level (TRL) scale has become part of the EU Horizon 2020 Work Programmes and in many countries and regions of Europe has been widely adopted in the context of ERDF (European Regional Development Fund) supported Research, Development and Innovation investments [3].

In the following table the definition for each TRL level according to European EU Horizon 2020 Work Programmes is reported:

MATURITY LEVEL	DESCRIPTION
TRL1	Basic principles observed
TRL2	Technology concept formulated
TRL3	Experimental proof of concept
TRL4	Technology validated in lab
TRL5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL7	System prototype demonstration in operational environment
TRL8	System complete and qualified
TRL9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Figure 2. TRL definition according to EU

In the current project, the target TRL for the REDHy system at the end of the project is 4 (i.e. technology validated in the lab).

Currently, there exist three prominent water electrolysis techniques that are commercially available (TRL 8-9): SOEC, PEMWE, and AWE. However, AEMWE is an emerging technology due to its potential for producing green hydrogen with higher efficiency. AEMWE merges the benefits of PEMWE and AWE, utilizing low-cost and readily available metals while maintaining excellent long-term stability. For this reason, it was selected also in the benchmarking analysis of this deliverable (see section 2.2).

Looking at the market, in Europe the operational manufacturing is around 12 GW_{el}/year. Alkaline technology represents 44% of operational European manufacturing capacity and PEMWE 54%. AEMWE and SOEC are emerging technologies, with around 1,5 GW_{el} of manufacturing capacity operational and under construction [4].

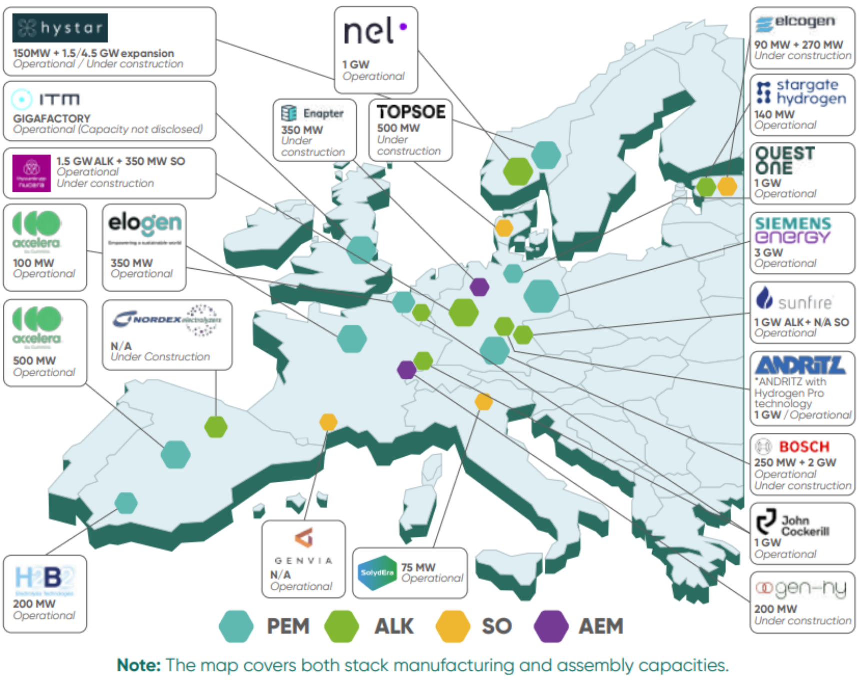


Figure 3. Main operational and under construction electrolyser manufacturing facilities in Europe [4]

2.2 Literature review: Life Cycle Assessment of water electrolysis technologies

In the context of the REDHy project, literature research was conducted on Life Cycle Assessment (LCA) studies, with particular attention to the construction phase of the most widespread electrolyzer technologies, as this is the main scope of this LCA study in the context of the REDHy project.

The objective was to identify existing methodologies, data availability, and key findings related to the environmental impacts associated with electrolyzers, including PEMWE, AWE, and AEMWE. These technologies were selected as the most like to the REDHy system.

The number of research papers analyzed is 52 (see Appendix A – Literature studies for the full list). To narrow the research and increase the adherence of the benchmarking analysis with the scope of the REDHy project, the following criteria were selected:

- **Presence of the Life Cycle Inventory for the construction phase of the electrolyzer.**
  The scope of the LCA of the REDHy system is assessing the potential environmental impacts associated also with the upstream material and construction phase of the electrolyzer system itself, to inform the partners and the external stakeholders on the impacts of electrolysis for hydrogen production also related to the upstream phase. Among the found articles only 50% included also the material inventory for the electrolyzer
- **Presence of an original Life Cycle Inventory for the construction phase of the electrolyzer.**
  Among articles in which the material inventory was found, only few of them had an original inventory (i.e. not retrieved from previous studies). The other articles were not included in the analysis because they did not add any significant data elaboration or simulation, therefore they were mere copies of previous articles. This is mainly because most available studies focus on the downstream phase, specifically the hydrogen production stage, while data related to the electrolyzer's construction phase are often restricted due to manufacturer confidentiality.
- **Presence of a disaggregated Life Cycle Inventory for the construction phase of the electrolyzer.**
  The data quality associated with the found articles in most of the time is not so high due to the confidentiality in reporting the exact data coming from the proprietary bill of materials of electrolyzers from industrial partners. Therefore, it happens often that the data is reported in a very aggregated way, not specifying datasets or if other assumptions were made to account for materials processing or manufacturing scraps.

Among the 52 articles found, only 16 were selected according to the selection criteria. Two tables are reported because not always the BoP is modelled in the studies. This constitutes another issue about data quality, since it hinders the possibility of knowing the entire system's actual potential impacts associated with hydrogen production.

Table 1. Number of articles in which Stack for each water electrolysis technology was assessed

Assessed technology, for the stack	Number of assessments[1]
AWE	12
PEM	14
AEM	2

[1] The number of assessments does not sum up to 16 (i.e. the number of articles) because in some articles multiple technologies are analyzed simultaneously.

Table 2. Number of articles in which Stack+BoP for each water electrolysis technology was assessed

Assessed technology, for the system	Number of assessments
AWE	6
PEM	10
AEM	0

It can be noted that the number of articles addressing the stack is higher than articles assessing the whole system, i.e. considering also the BoP.

Furthermore, AEMWE LCA assessment was found in only 2 articles, focused only on the stack.

2.2.1 Raw materials and manufacturing

The average carbon footprint associated with the construction phase of the electrolyzer across all technologies is:

- About 240 kg CO_2-eq/kW for the stack

The impact of the electrolyzer system (i.e., stack and Balance of Plant) is not reported due to the limited number of studies analyzing this aspect, making the available data insufficient to represent an average value. Moreover, for AEMWE technology, no literature data were found regarding the Bill of Materials associated with the Balance of Plant.

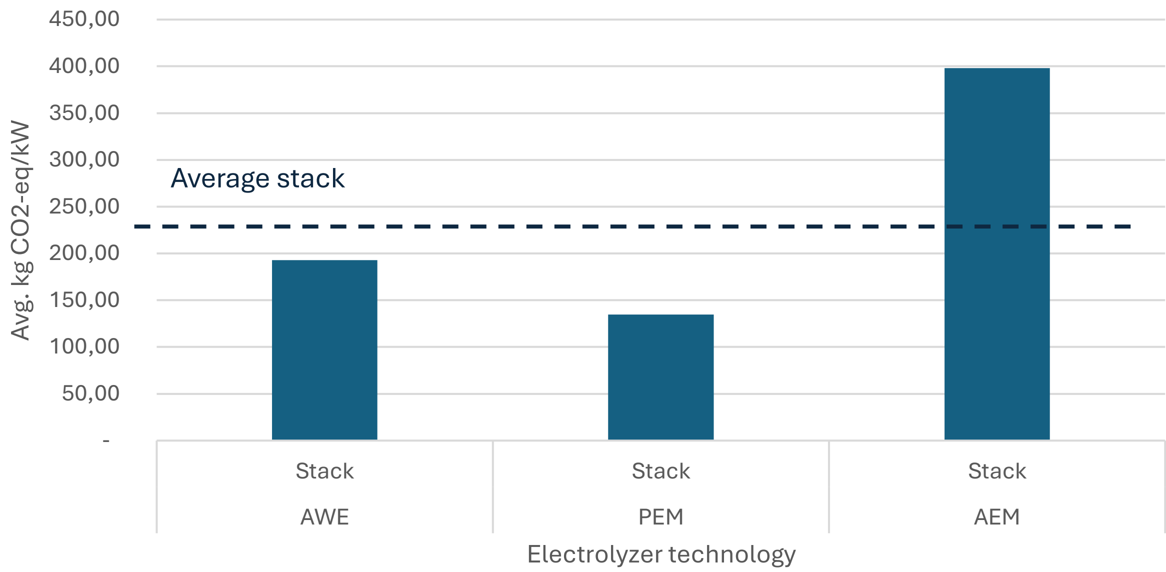


Figure 4. Electrolyzer construction phase – Carbon footprint benchmarking across technologies

2.2.2 Use phase

The major consumptions associated with the operation of water electrolyzer for hydrogen production are:

- Electricity
- Water
- Electrolyte

2.2.2.1 Electricity and electrolyte consumption

Among the reviewed articles, electricity consumption data for the system were reported as follows:

Technology	# literature assessments with stack electrical data	# literature assessments with BoP electrical data
AWE	10	1
PEM	14	3
AEM	2	0

The average for the stack is 50 kWh/kg H_2 for all technologies, while the average of total system energy consumption has a low reliability due to the small sample size of data about BoP electrical consumption.

Other KPIs related to benchmarking are reported in Table 3**Errore. L'autoriferimento non è valido per un segnalibro.**. Because AEMWE technology is still at an early stage of development, many KPIs are not yet well-documented in the literature.

Table 3. Other use phase KPIs from benchmarking

Technology	Average electrolyte consumption [g KOH[2]/kg H2]	Average degradation [mV/h]	Average stack lifetime [h]	Average lifetime, system components [y]
AWE	5,49	0,0013	70.000,00	20
PEM	-	0,0003	81.666,50	20
AEM	-	-	20.000,00	-

2.2.2.2 Water consumption

From water electrolysis reaction stoichiometry, 9 kg of deionized water is required to produce 1 kg of hydrogen. This value is the most reported in the analyzed articles. Anyway, the average amount reported in the reviewed articles is slightly higher and it is reported in Table 4.

Regardless of the feedstock, the water supplying an electrolyzer must first be purified and demineralized. Therefore, considering the potential water losses and the use of water for cleaning the equipment, the actual water required to produce 1 kg of hydrogen by electrolysis is estimated at 13.5–15.0 kg H_2O/kg H_2 [5]

Furthermore, water is used as input also by other components of the BoP. In relation to this consumption only one article was found indicating also the water consumption associated with

[2] For AWE, the indicated electrolyte in literature is always KOH.

the cooling and compressor system, being equal to 88,1 kg H_2O/kg H_2 for both AWE and PEM technologies [6].

Regarding water as output, only one article was found reporting the amount of wastewater generated during the operation of the electrolyzer, for all the three analyzed technologies, as reported in Table 4 [7]. Nevertheless, due to the unique sample size of these consumption data, the reliability is limited.

Table 4. Water consumption figures from benchmarking

Technology	Average water consumption[3] [kg H_2O/kg H_2]	Wastewater [kg H_2O/kg H_2]
AWE	11,58	0,36
PEM	11,35	4,51
AEM	13,02	0,35

2.2.3 End of Life

Among the reviewed articles only four have a dedicated section to the EoL treatment of electrolyzer components.

In Table 5. EoL scenarios found in literature a brief description of how EoL was managed is reported:

Table 5. EoL scenarios found in literature

Article 1st author	Article Title	Year of publication	EoL treatment short decription	EoL modelling
Hoppe, A.	Reducing Environmental Impacts of Water Electrolysis Systems by Reuse and Recycling: Life Cycle Assessment of a 5 MW Alkaline Water Electrolysis Plant	2025	Assessment of realistic recycling scenarios that highlight potential material recovery and component reuse after the system's 20-year lifespan.	77% of materials in the AWE system can be recycled or reused, though the substantial environmental impacts of certain components, particularly the inverter and nickel, necessitate ongoing research and improved recycling technologies.
Rivera, X.	Environmental sustainability of renewable hydrogen in comparison with	2018	This study assumes that the system components are landfilled	The recycling rates for the metals are as follows: aluminium 90%, steel 85% and copper 45%. Platinum

[3] Water consumption related to the stack only, i.e. water required by the electrolysis reaction.

	conventional cooking fuels		at the end of their useful lifetime. This assumption is deemed reasonable as the deployment of the system is assumed to be in developing economies where recycling facilities are lacking.	and iridium used in the electrolyser are assumed to be 100% recycled. All other materials are landfilled.
Gerloff, N.	Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production	2021	Since there are hardly any recycling processes for the disposal phase as well as only limited waste treatment and disposal processes for materials available in the database, EoL processes have been selected to model the disposal phase.	13 selected disposal processes from the ecoinvent database v.3.5 have been considered for metals, plastics cable and printing boards.
Lotric, A.	Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies	2021	EoL assessments show that the environmental impacts of the manufacturing phase can be substantially reduced by using the proposed EoL strategies.	Manual dismantling was applied for all subsystems and components that cannot be reused. Recycling rates for different materials were defined based on data from the recycling-industry sector. Energy extraction and landfills were only used in cases

				where reuse or recycling was not possible, or no other data were available for the EoL.

2.3 Life Cycle Assessment frameworks for hydrogen production technologies

The main outcome of the JRC technical report "Life Cycle Assessment of Hydrogen and Fuel Cell Technologies" published in 2020 [8] is that currently the available deliverables from previous projects are lacking information needed to perform meaningful comparison across different LCAs of hydrogen technologies.

Indeed, to ensure consistency and comparability across different Life Cycle Assessments (LCAs), it is essential to establish a standardized approach for conducting them (at present, there are no Product Category Rules (PCRs) available to perform LCAs on water electrolysis electrolyzers.

The review conducted in the context of WP7 showed that only guidelines and deliverables from previous EU-funded projects are available, focusing on establishing a common framework for developing LCAs of water electrolyzers used in hydrogen production. These include:

- 2011 – FC4Hy - Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies [9]
- 2023 – ISO/TS 19870:2023 - Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate [10]
- 2024 - SH2E - D2.2 Definition of FCH-LCA guidelines, WP2 Reformulation of current guidelines for Life Cycle Assessment [11]

The FC-HyGuide project responds to this need by providing a guided document on how to perform every step of a LCA for hydrogen production and fuel cell technologies. Here the focus was mainly related to fuel cells and the guidelines focused only on 4 impact categories, therefore it is not used as main reference in this deliverable.

The ISO/TS 19870:2023 standard is a high-level generic standard related to H2 production; therefore, it does not cover the topics related to LCA of capital goods.

The last one, SH2E, is an EC funded project that closed on 30 June 2024**,** aiming at creating guidelines for life cycle sustainability assessment of hydrogen systems. This document provides methodological guidance on how to perform a Life Cycle Assessment (LCA) of fuel cells and hydrogen (FCH) systems. It recalls international standards and reference documents on LCA in general (ISO 14040, ISO 14044, and ILCD handbook), as well as previous FC-HyGuide.

Based on this project the JRC published a checklist document to be used as reference when drafting LCA deliverable of funded project.
Being the most up-to-date and comprehensive reference, information reported in this deliverable is aligned with the JRC LCA Checklist [12].

3. Life Cycle Assessment of REDHy technology

3.1 Goal of the study

The Intended application of the study is to assess the potential environmental impacts of the REDHy system according to ISO 14040 and 14044. This study has been commissioned as defined in the Grant Agreement of the REDHy project (101137893) funded by the European Commission under the Clean Hydrogen Joint Undertaking in the HORIZON-JTI-CLEANH2-2023-1 call.

The REDHy system is an ex-ante new technology for hydrogen production through water electrolysis, expected to reach TRL 4 at the end of the project.

The REDHy system is composed of:

- Electrolyzer stack: composed of 5 cells (at current status of the project each cell dimension is 25 cm^2); each cell is made of 3D printed porous graphite electrodes, AROC and CROC redox mediators and a fluorine-free PEM membrane.
- Electrolyzer BoP: comprising all the auxiliary mechanical and electronic components needed to produce hydrogen.
- External reactors with HER and OER catalysts for the reduction and oxidation reactions.

In Figure 5 the REDHy concept is shown:

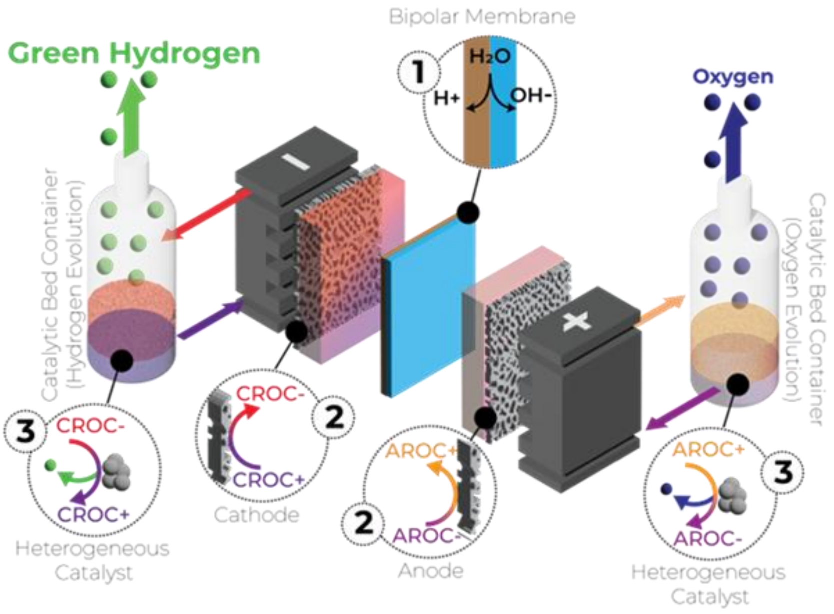


Figure 5. REDHy system design concept

3.1.1 Application situation

Due to the low TRL of the REDHy system, the results of this study will not be used for policy support regarding the implementation of hydrogen production pathways from an environmental perspective. Being a preliminary assessment, this document is to be considered as just informative for the project partners. The related results are expected to support decisions only at micro scale in the context of REDHy technology development within the project.

3.1.2 Reason for carrying out the study and target audience

The reason for carrying out this study is to illustrate to project partners and external stakeholders the potential environmental impacts of a novel hydrogen producing electrolyzer, from cradle-to-grave, and address potential areas for improvement already at an early development stage, given the increasing importance of hydrogen in the decarbonization of hard to abate sectors.

3.1.3 Modelling approach

The LCA modeling approach is attributional LCA. This approach models the state of a system at a particular moment in time, attributing inputs and outputs to the product's functional unit.

3.2 Scope of the study

3.2.1 Functional unit

The functional unit is the production of one 1 kg H2 through the REDHy system, according to latest project partners' developments at the time of this deliverable publication.

The actual lifetime of the system is still not yet defined at the current stage of the project, but project target indicates at least 1200 hours of operation of the system.

3.2.2 System boundaries

The system boundaries are cradle-to-grave, including life cycle stages from raw material extraction and processing, manufacturing, delivery to final users, use phase and end of life.

- Raw Materials Supply and Processing – Includes the chemical compounds and materials required to manufacture the product, according to its chemical composition. Furthermore, processing of raw materials is considered to account for producing intermediate products (i.e. generic datasets are used to account for manufacturing processing of extracted raw materials).
- Manufacturing energy consumption – Covers electricity, fuels and process consumables needed to produce the product in its active final form.
- End of Life – Accounts for specific pre-treatment, core treatment processes and transportation required to reach the disposal site at the end of life. To account for recycling the cut-off approach has been used.

This study applies cut-off. See section 3.2.2.1 for details.

The cradle-to-grave system boundaries are reported in Figure 6:

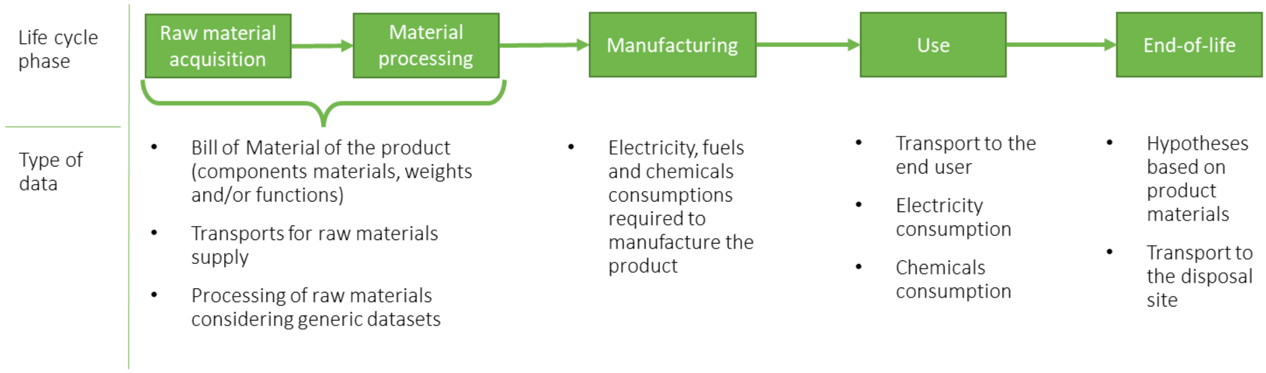


Figure 6. System boundaries

At current project status information on electrode/stack components degradation is not available, therefore the consumptions related to maintenance operations are not considered in the present study.

3.2.2.1 Cut-off

- Transport associated with components transportation from their production site to the assembly site of the stack and/or system.
- Packaging of all the components within the system.
- Maintenance associated with the REDHy system[4].
- Transport for maintenance operations.
- Consumptions related to the installation and deinstallation of the system.

3.3 Impact assessment

The assessment is performed according to the following technical specifications:

- LCA software: SimaPro 10.10
- LCA database for background data: ecoinvent 3.11.
    - Regarding processes of the background system the cut-off system model from ecoinvent is used.
    - Whenever available, datasets have been selected considering that the REDHy system is manufactured in Europe.
- LCA characterization method: Environmental Footprint 3.1 (adapted) V1.03 / EF 3.1 normalization and weighting set
- LCA impact categories analyzed:

Impact category	Unit of measure
Acidification	mol H+ eq
Climate change	kg CO2 eq
Climate change - Biogenic	kg CO2 eq
Climate change - Fossil	kg CO2 eq

[4] This cut-off is applied because at the current stage of development no data on electrode or Stack and BoP degradation are available.

Climate change - Land use and LU change	kg CO2 eq
Ecotoxicity, freshwater - part 1	CTUe
Ecotoxicity, freshwater - part 2	CTUe
Ecotoxicity, freshwater - inorganics	CTUe
Ecotoxicity, freshwater - organics - p.1	disease inc.
Ecotoxicity, freshwater - organics - p.2	kg N eq
Particulate matter	kg P eq
Eutrophication, marine	mol N eq
Eutrophication, freshwater	CTUh
Eutrophication, terrestrial	CTUh
Human toxicity, cancer	CTUh
Human toxicity, cancer - inorganics	CTUh
Human toxicity, cancer - organics	CTUh
Human toxicity, non-cancer	CTUh
Human toxicity, non-cancer - inorganics	kBq U-235 eq
Human toxicity, non-cancer - organics	Pt
Ionising radiation	kg CFC11 eq
Land use	kg NMVOC eq
Ozone depletion	MJ
Photochemical ozone formation	kg Sb eq
Resource use, fossils	m3 depriv.
Resource use, minerals and metals	mol H+ eq
Water use	kg CO2 eq

3.3.1 Assumptions and limitations

The assumptions that have been made in the study are detailed in each related paragraph. The LCA limitations are detailed in section 3.8.1. Moreover, the results cannot be compared to other commercial electrolyser systems due to the different TRL and the very specific conditions in which the REDHy system at lab scale was tested.

3.4 Inventory: construction and EoL

In this chapter, all the relevant input flows included in the study are reported, as communicated by the project partners.

Data related the Raw material and processing, Manufacturing, and End of Life are addressed separately for each WP who is working on it. End-of-Life was modelled using the 'cut-off' approach. Therefore, the recovery and upgrading of products at the end of life are 'cut-off' (no credits were given to the system for secondary raw material or energy recovery in the downstream), while the collection, transport and pre-treatment are included in the modelling.

Data related to the transportation to the end user and the use phase of the REDHy system are addressed separately in the Section 3.6 and Section 3.6.

At this stage of early development of the REDHy system, output flows have not been investigated yet[5].

3.4.1 Membrane development (developed by WP3)

Currently different membrane options have been developed and tested by WP3:

1. High-performance engineering plastic (Polysulfone (PSU) or Polyethersulfone (PES) based)
2. Polymer produced by CENmat, modified for proton conductivity

The steps required to manufacture the membrane 1) are depicted in Figure 7:

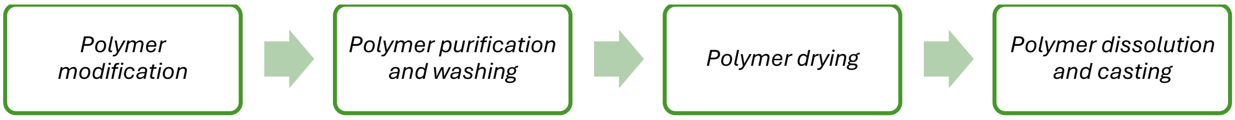


Figure 7. Membrane 1) manufacturing steps

The steps required to manufacture the membrane 2) are depicted in Figure 8:

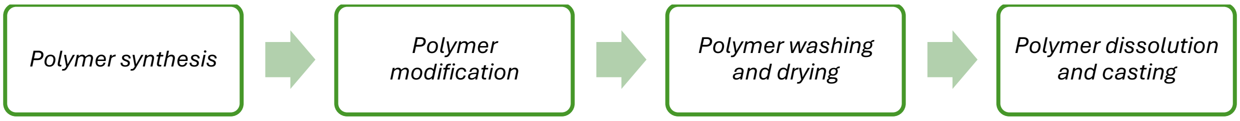


Figure 8. Membrane 2) manufacturing steps

The following materials are used to manufacture the membrane 1):

Table 6. LCI for Raw Materials Supply and Manufacturing of High-performance engineering plastic membrane 1)

Input data	Dataset	Quantity	UoM
Reference flow: 2000 cm2 membrane			
Polymer		15	g
Inorganic acid		300	g
Water ultrapure		5	kg
Organic solvent		150	g
Electricity, heating plate	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	15,3	kWh
Electricity, stirring		0,07	
Electricity, mixer		0,08	
Electricity, drying oven		24	
Electricity, heating plate		5,1	

Table 7. LCI for Raw Materials Supply and Manufacturing of CENmat membrane 2)

Input data	Dataset	Quantity	UoM

[5] See section 3.8.2 for further details.

Reference flow: 2800 cm2 membrane			
Polymer		15	g
Polymer modification compound 1		15	g
Polymer modification compound 2		0,15	g
Organic solvent 1		30	g
Alcol		0,789	kg
Inorganic acid		10	g
Water ultrapure		5	kg
Organic solvent 2		150	g
Electricity, heating plate	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	5,1	kWh
Electricity, oven		24	
Electricity, polymer modification		5,1	
Electricity, stirring		0,07	
Electricity, mixer		0,08	
Electricity, drying oven		24	

At the end of life, it has been considered that the material is sent to recycling in both cases. To account for the transportation to the disposal site 1000 km has been assumed to be made by truck. The following ecoinvent dataset has been used:

- *Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*

3.4.2 Electrode development (WP4)

The steps required to manufacture the electrode substrate are depicted in Figure 9:

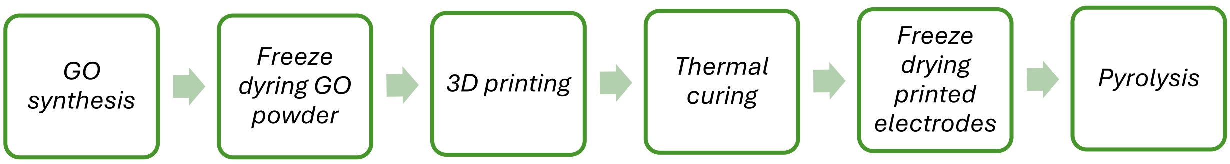


Figure 9. GO electrode manufacturing steps

The following materials are used to manufacture the electrode:

Table 8. LCI for Raw Materials Supply and Manufacturing of GO ink synthesis

Input data	Dataset	Quantity	UoM
Reference flow: 12,5 mL of GO ink			
Graphite	*Graphite {GLO}| market for graphite | Cut-off, S*	3	g

Sulfuric acid		*Sulfuric acid {RER}| market for sulfuric acid | Cut-off, S*	0,662	kg
Phosphoric acid		*Phosphoric acid, fertiliser grade, without water, in 70% solution state {RER}| market for phosphoric acid, fertiliser grade, without water, in 70% solution state | Cut-off, S*	0,0752	kg
Potassium permanganate		*Potassium permanganate {GLO}| market for potassium permanganate | Cut-off, S*	18	g
Hydrochloric acid		*Hydrochloric acid, without water, in 30% solution state {RER}| market for hydrochloric acid, without water, in 30% solution state | Cut-off, S*	3,45	kg
Electricity	Hot plate	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	15,3	kWh
	Centrifuge		12	

Table 9. LCI for Raw Materials Supply and Manufacturing of GO electrode

Input data		Dataset	Quantity	UoM
Reference flow: 25 cm2 of electrode				
GO ink		*GO synthesis process*	4	mL
Nitrogen		*Nitrogen, liquid {RER}| market for nitrogen, liquid | Cut-off, S*	3,42E3	g
Electricity	Freeze drying of the powder	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	57,6	kWh
	Printer power		0,24	
	Vacuum oven		4,35	
	Freeze drying of the electrode		57,6	
	Pyrolysis		65,7	

At the end of life, it has been considered that the material is sent to landfill as inert. To account for the transportation to the disposal site 1000 km has been assumed to be made by truck. The following table highlights the quantities and datasets considered:

Table 10. End-Of-Life LCI for the GO electrode

Input data	Dataset	Quantity	UoM
Reference flow: 3,125 g			
Graphite oxide electrode	*Inert waste, for final disposal {CH}| treatment of inert*	3,125	g

	waste, inert material landfill | Cut-off, S		
Transport to disposal site	*Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*	0,003125*1000	kgkm

3.4.3 Catalysts development for HER and OER (WP5)

Currently different catalysts options have been developed and tested by WP5:

- For OER: NiFeOxHy and NiMnOxHy (alkaline environment)
- For HER: MoS2 and MoS2/C (acidic environment – BPM membrane) and NiMo, NiMo/C (alkaline environment – AEM membrane as backup solution)

In this deliverable the following options have been selected from WP5 and assessed through LCA:

- MoS2
- MoS2/C
- NiFe
- NiMo

WP 5 is also in charge of testing on the single cell, and later in the project on the whole REDHy system. See section 3.6 for the data related to the use phase of a single cell.

3.4.3.1 MoS2 catalyst

The steps required to manufacture the catalysts are depicted in Figure 10:

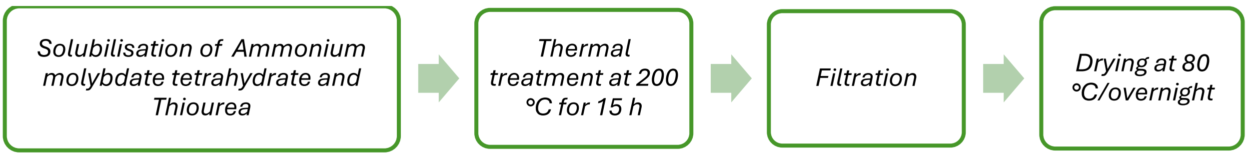


Figure 10.MoS2 catalysts manufacturing steps

The following materials are used to manufacture the catalyst:

Table 11.LCI for Raw Materials Supply and Manufacturing of MoS2 catalyst

Input data	Dataset	Quantity	UoM
Reference flow: 2 g of MoS2 catalyst			
Thiourea (for solubilization + filtration)	*Thiourea, RER, Wikipedia[6]*	5,43+702,5	g

[6] Ad hoc dataset. Modeled according to the stoichiometry of the reaction to produce thiourea, link here

Ammonium molybdate tetrahydrate for solubilization		*Ammonium molybdate tetrahydrate, RER, Nanjing University*[7]	2,1	g
Ultrapure water for solubilization		*Water, ultrapure {RER}| market for water, ultrapure | Cut-off, S*	0,2	kg
Electricity	Hot plate magnetic stirrer for solubilization	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	6,3	kWh
	Reduction reactor for thermal treatment		12,16	kWh
	Filtration pump		0,6	kWh
	Oven for drying		24	kWh

At the end of life, it has been considered that the material is recycled. Therefore, only sorting and compacting of the metals is considered in the analysis. To account for the transportation to the recycling facility 1000 km has been assumed to be made by truck.

Table 12. LCI for EoL of MoS2 catalyst

Input data	Dataset	Quantity	UoM
Reference flow: 2 g of MoS2 catalyst			
Catalyst metal sorting	*Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, S*	2	g
Transport to disposal site	*Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*	0,002*1000	kgkm

[7] Ad hoc dataset. Modeled according to the stoichiometry of the reaction to produce ammonium molybdate tetrahydrate, link here

3.4.3.2 MoS2/C catalyst

The steps required to manufacture the catalysts are depicted in Figure 11:

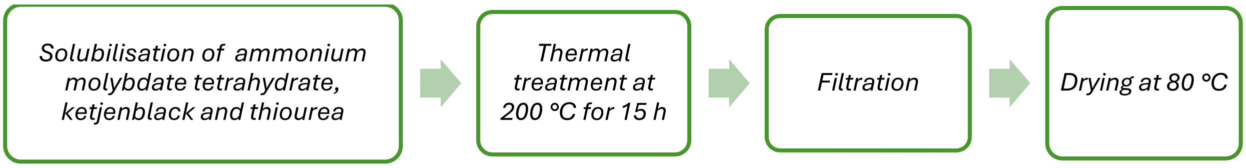


Figure 11. MoS2/C catalysts manufacturing steps

The following materials are used to manufacture the catalyst:

Table 13.LCI for Raw Materials Supply and Manufacturing of MoS2/C catalyst

Input data		Dataset	Quantity	UoM
Reference flow: 2 g of MoS2/C catalyst				
Thiourea (for solubilization + filtration)		*Thiourea, RER, Wikipedia*	5,43+702,5	g
Ammonium molybdate tetrahydrate for solubilization		*Ammonium molybdate tetrahydrate, RER, Nanjing University*	2,1	g
Carbon black		*Carbon black {GLO}| market for carbon black | Cut-off, S*	0,86	g
Ultrapure water for solubilization		*Water, ultrapure {RER}| market for water, ultrapure | Cut-off, S*	0,2	kg
Electricity	Hot plate magnetic stirrer for solubilization	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	6,3	kWh
	Reduction reactor for thermal treatment		12,16	kWh
	Filtration pump		0,6	kWh
	Oven for drying		24	kWh

At the end of life, it has been considered that the material is recycled. Therefore, only sorting and compacting of the metals is considered in the analysis. To account for the transportation to the recycling facility 1000 km has been assumed to be made by truck.

Table 14. LCI for EoL of MoS2/C catalyst

Input data	Dataset	Quantity	UoM
Reference flow: 2 g of MoS2/C catalyst			

Catalyst metal sorting	*Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, S*	2	g
Transport to disposal site	*Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*	0,002*1000	kgkm

3.4.3.3 3.2.2.3 NiFe catalyst

The steps required to manufacture the catalysts are depicted in the following figure

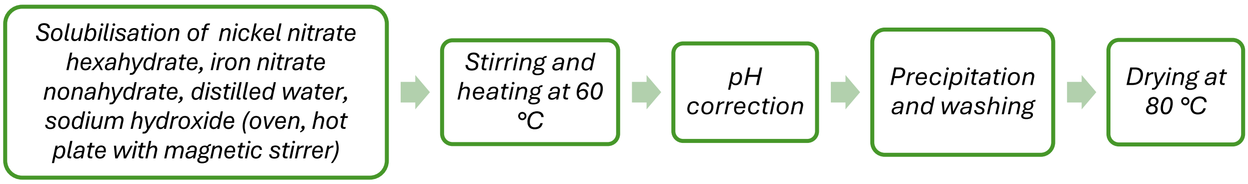


Figure 12. NiFe catalysts manufacturing steps

The following materials are used to manufacture the catalyst:

Table 15.LCI for Raw Materials Supply and Manufacturing of NiFe catalyst

Input data	Dataset	Quantity	UoM
Reference flow: 2 g of NiFe catalyst			
Nickel nitrate hexahydrate for solubilization	*Nickel nitrate hexahydrate, RER, Glogic*[8]	5	g
Iron nitrate nonahydrate for solubilization	*Iron nitrate nonahydrate, GLO, Wikipedia*[9]	1,22	g
Sodium hydroxide for solubilization	*Sodium hydroxide, without water, in 50% solution state {RER}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, S*	10	g
Distilled water for solubilization	*Water, decarbonised {RoW}| market for water, decarbonised | Cut-off, S*	0,5	kg
Sodium nitrate for filtration	*Sodium nitrate {GLO}| market for sodium nitrate | Cut-off, S*	2,26	kg
Electricity – Hot plate magnetic		6,3	kWh

[8] Ad hoc dataset. Reference: 2019 - Glogic - RSC Advances - LCA of emerging Ni–Co hydroxide charge storage electrodes
Supplementary Materials, Table S3

[9] Ad hoc dataset. Modeled according to the stoichiometry of the reaction to produce iron nitrate nonahydrate, link here

	stirrer for solubilization	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*		
	Filtration pump		0,6	kWh
	Oven for drying		24	kWh

At the end of life, it has been considered that the material is recycled. Therefore, only sorting and compacting of the metals is considered in the analysis. To account for the transportation to the recycling facility 1000 km has been assumed to be made by truck.

Table 16. LCI for EoL of NiFe catalyst

Input data	Dataset	Quantity	UoM
Reference flow: 2 g of NiFe catalyst			
Catalyst metal sorting	*Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, S*	2	g
Transport to disposal site	*Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*	0,002*1000	kgkm

3.4.3.4 3.2.2.3 NiMo catalyst

The steps required to manufacture the catalysts are depicted in Figure 13:

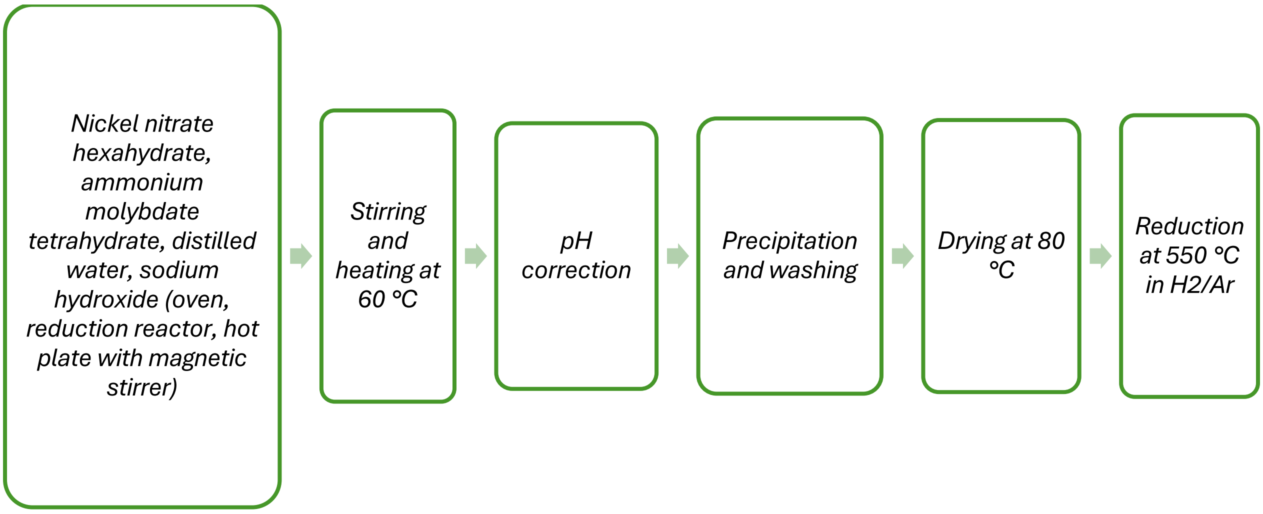


Figure 13. NiMo catalysts manufacturing steps

The following materials are used to manufacture the catalyst:

Table 17.LCI for Raw Materials Supply and Manufacturing of NiMo catalyst

Input data	Dataset	Quantity	UoM

Reference flow: 2 g of NiMo catalyst				
Nickel nitrate hexahydrate for solubilization		*Nickel nitrate hexahydrate, RER, Glogic*	4,39	g
Ammonium molybdate tetrahydrate for solubilization		*Ammonium molybdate tetrahydrate, RER, Nanjing University*	2,66	g
Sodium hydroxide for solubilization		*Sodium hydroxide, without water, in 50% solution state {RER}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, S*	10	g
Distilled water for solubilization		*Water, decarbonised {RoW}| market for water, decarbonised | Cut-off, S*	0,2	kg
Sodium nitrate for filtration		*Sodium nitrate {GLO}| market for sodium nitrate | Cut-off, S*	1,81	kg
Electricity	Hot plate magnetic stirrer for solubilization	*Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, S*	6,3	kWh
	Filtration pump		0,6	kWh
	Oven for drying		24	kWh
	Reduction reactor		12,6	kWh

At the end of life, it has been considered that the material is recycled. Therefore, only sorting and compacting of the metals is considered in the analysis. To account for the transportation to the recycling facility 1000 km has been assumed to be made by truck.

Table 18. LCI for EoL of NiMo catalyst

Input data	Dataset	Quantity	UoM
Reference flow: 2 g of NiMo catalyst			
Catalyst metal sorting	*Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, S*	2	g
Transport to disposal site	*Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*	0,002*1000	kgkm

3.4.4 Stack and BoP components design (WP6)

WP 6 oversees developing the stack and BoP components of the REDHy system. At the time of uploading Deliverable 7.1, work on characterizing all the stack and BoP components had not been finished yet. Consequently, there are different options for materials that have been taken into consideration.

For the bipolar plates (BPPs) four different options are currently under investigation:

1. Both anodic and cathodic BPPs made of composite material (graphite/PP)
2. Both anodic and cathodic BPPs made of stainless steel (SS)
3. Both anodic and cathodic BPPs made of nickel (Ni)
4. Differentiation between anodic BPP material (SS) and cathodic BPP material (composite graphite/PP)

For the gasket two materials are under investigation: Viton and EPDM. Since the Viton option has a higher material weight it has been considered conservatively in the analysis.

Similarly, for the insulation panel two materials are under investigation: Polysulfone (PSU) and PP. Since the PSU option has a higher material weight it has been considered conservatively in the analysis.

In Table 19 the number of pieces for each component within the REDHy stack and BoP is reported. For the BPPs, the different options are mutually exclusive.

For the stack and BoP components the consumptions related to the manufacturing are not known as primary data since they are supplied by external vendors. Therefore, generic ecoinvent datasets are applied, accounting for metals sheet rolling and metal working.

See Appendix B - LCI for the detailed modelling of each item.

Table 19. LCI for REDHy stack and BoP components

<table>
<tr><th colspan="2">Item</th><th>Quantity [pc]</th></tr>
<tr><td colspan="3">Reference flow: 1 REDHy stack and BoP system</td></tr>
<tr><td rowspan="4">Bipolar plate</td><td>Option 1: Graphite/PP</td><td rowspan="3">10</td></tr>
<tr><td>Option 2: Nickel</td></tr>
<tr><td>Option 3: Stainless Steel</td></tr>
<tr><td>Option 4: Anode Stainless steel, cathode graphite/PP</td><td>5 anode SS and 5 cathode graphite BPs</td></tr>
<tr><td colspan="2">Endplate</td><td>2</td></tr>
<tr><td rowspan="2">Reactor</td><td>Body</td><td>2</td></tr>
<tr><td>Flange</td><td>2</td></tr>
<tr><td rowspan="2">Tank</td><td>Body</td><td>2</td></tr>
<tr><td>Flange</td><td>2</td></tr>
<tr><td rowspan="2">Housing</td><td>Top</td><td>1</td></tr>
<tr><td>Box</td><td>1</td></tr>
</table>

Electrolyte distributor	4
Swagelok SS-6M0-1-2RT	20
Swagelok SS-14M0-1-8RS	4
Stack fixing edge	2
Connector, current supply	2
Calorplast heat exchanger	2
Gasket	20
Insulation panel	2
Tubes, 6 mm diameter	20
Tubes, 14 mm diameter	4
BoP system	1

At the end of life, the scenarios in Table 20 have been considered:

Table 20. EoL life cycle phase scenarios

Material classification	REDHy system scenario			
	BP option 1: both sides graphite/PP	**BP option 2: both sides SS**	**BP option 3: both sides Ni**	**BP option 4: Anode SS/Cathode graphite/PP**
Metals [kg]	37,69	42,20	42,87	39,94
Plastic, to incineration [kg]	0,14	0,14	0,14	0,14
Plastic, to recycling [kg]	6,72	6,72	6,72	6,72
Sum of components weight [kg]	44,55	49,06	49,73	46,80

For metals sent to recycling, only sorting and compacting of the metals is considered in the analysis.

Plastics sent to recycling are not accounted for[10]. Plastic incineration has been conservatively modelled considering hazardous waste incineration.

To account for the transportation to the disposal facility 1000 km has been assumed to be made by truck. For each REDHy system scenario (“*i*”) the following inventory applies:

Table 21.LCI for EOL treatment of the different REDHy stack and BoP scenarios

Input data	Dataset	Quantity	UoM
Reference flow: 1 REDHy stack and BoP system$_i$			

[10] According to the cut off approach for EoL, as explained in 3

Metals	*Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, S*	$Metals_i$	kg
Plastic components incineration	*Hazardous waste, for incineration {Europe without Switzerland}| market for hazardous waste, for incineration | Cut-off, S*	Plastics, to $incineration_i$	kg
Transport to disposal site	*Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*	Sum of components $weight_i$ *1000	kgkm

3.5 Inventory: Transport to end user

A scenario based on assumptions was assumed in the study to account for REDHy transportation from the manufacturing facility up to the final end-user.

The following assumptions have been made:

- Transportation by truck, selecting the ecoinvent dataset *Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 {RER}| market for transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 4 | Cut-off, S*
- Transportation distance: 1000 km.

To account for transportation the average weight of the REDHy system among the different options reported in Section 3.7.6 have been selected, being equal to 47,56 kg.

3.6 Inventory: Use phase

Table 22 summarizes the project targets from the Grant Agreement related to the operational performance of the REDHy system:

Table 22. Target values for REDHy use phase

Data	Target value	UoM
Surface area[11]	>100	cm^2
Stack power	>1,5	kW
Degradation	0,1%/1000 h	-
Current density	1,5	A/cm^2
Energy consumption	48	kWh/kg H_2
Operational hours	1200	hours

[11] The present study considers that each cell is 25 cm^2

The following table highlights the main data associated with single cell testing.

Table 23. Performance data of pilot cell set up

Input data		Value	UoM
Current density		1	A/cm^2
Voltage		2,1-2,2	V
Energy consumption		0,0105-0,0115	kWh/cell
Produced H2		34,1	cc/min
Electrolyte		20	mL
Thiourea and/or ultrapure water waste	MoS2 catalyst	0,7	L
	MoS2/C catalyst	0,7	L
	NiFe catalyst	1	L (only water)
	NiMo catalyst	1	L (only water)

At the time of uploading the present deliverable, the work on characterizing electrode degradation under operational conditions had not yet begun. Consequently, there is currently insufficient experimental data from tests.

To account for degradation at this stage, the target value for degradation has been used when assessing the use phase performances of the REDHy system. Updated, actual, information will be included in future deliverables as relevant test results become available.

Similarly, in the present study the target operational lifetime has been considered, but actual information from durability tests should preferably be included in future assessment.

The average amount of wastewater produced by the different catalysts options has been considered in the analysis.

All the flows quantities have been referred to the production of 1 kg H2.

The ecoinvent datasets used in the analysis are:

- For photovoltaic electricity: *Electricity, low voltage {RoW}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, S*
- For windy electricity: *Electricity, high voltage {RoW}| electricity production, wind, <1MW turbine, onshore | Cut-off, S*
- For KOH: *Potassium hydroxide {GLO}| market for potassium hydroxide | Cut-off, S*
- For ultrapure water: *Water, ultrapure {RER}| market for water, ultrapure | Cut-off, S*
- For wastewater: *Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, S*

3.7 Life Cycle Impact Assessment

For the sake of clarity, in this chapter the LCIA results are reported in charts only for the impact categories that were considered having higher priority in the FC-HyGuide: global warming potential (i.e. climate change considering EF method), acidification potential, eutrophication potential, abiotic depletion (i.e. resource use, minerals and metals considering EF method).

In Appendix C – Results the results for all 27 impact categories are reported.

3.7.1 Redox mediators impact assessment results

Currently different redox mediators are under investigation. The impact assessment for the whole REDHy system has been performed considering the mediators loading values communicated by CNR (WP5) according to the most recent tests performed.

The load of each mediator tested by CNR needed to obtain a concentration of 0,06 M is reported in Table 24:

Table 24. Mediators load

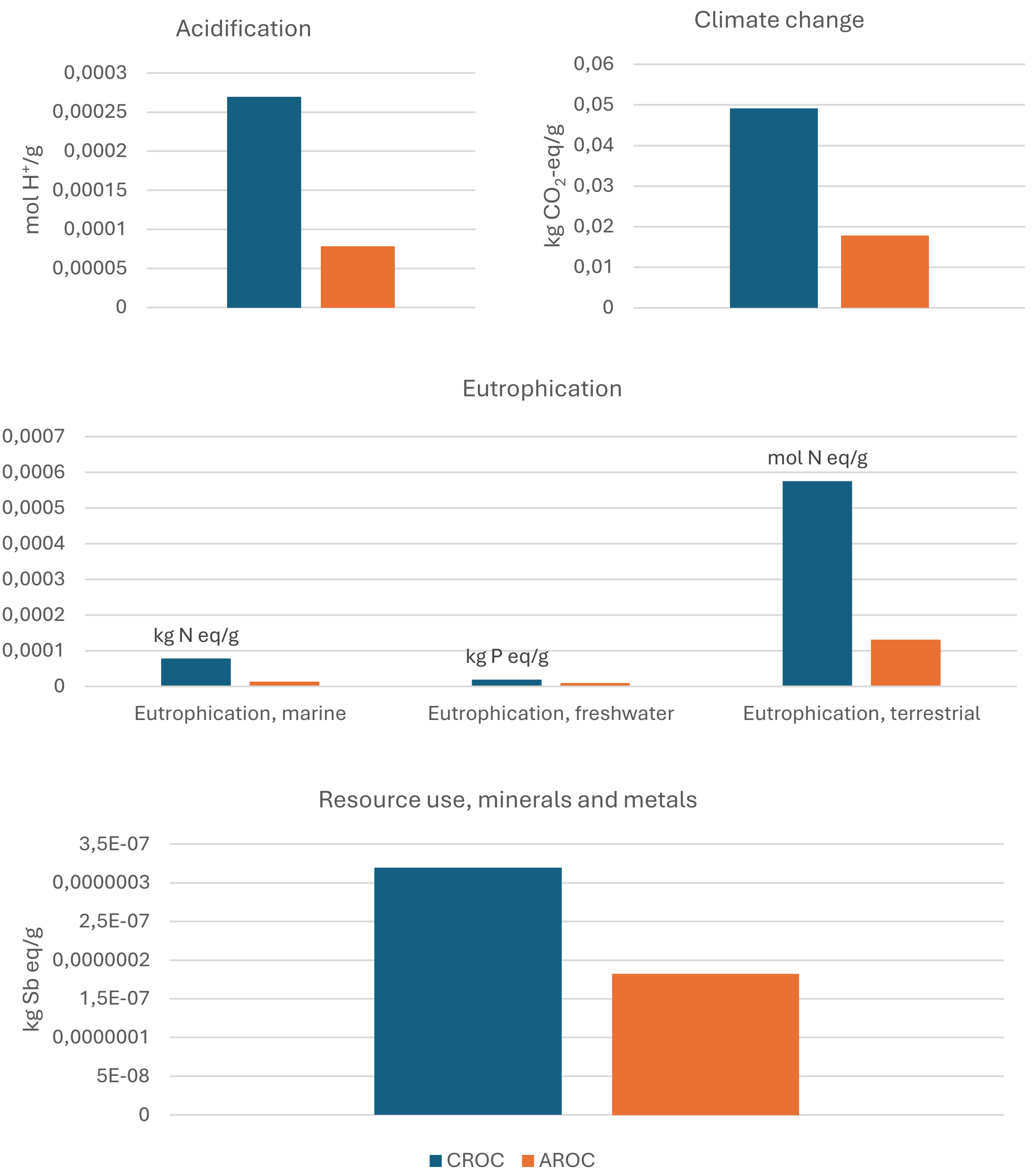
Mediator	Value	UoM
CROC – DHSP (commercial)	0,35	g/20 mL of KOH 1 M
AROC - $K_3Fe(CN)_6$ (commercial)	0,39	
CROC – AB3	0,48	
CROC – AB4	0,52	
CROC – AB6	0,43	

At the time of this deliverable, the AROC AC6, for which UPV (WP2) provided the LCI data, has not been tested by CNR. Therefore, the load of the commercial $K_3Fe(CN)_6$ AROC that has been already tested by CNR was used as proxy. For the CROC AB3 was considered in accordance with the LCI provided by UPV.

To make comparison the results in the following charts are reported by gram of mediators. The full results obtained for the REDHy system (i.e. considering the load) can be found in Appendix C – Results.

AROC shows minor unitary impacts in all the analyzed impact categories with respect to CROC. In the CROC the highest impact is mainly due to the higher materials impact and higher electricity consumption (e.g. in acidification potential and climate change the CROC material impact is about 80% higher than AROC materials, and electricity is about 50% higher with respect to the electricity impacts associated with AROC production).

Moreover, given the higher concentration of CROC AB3 mediator in the solution, also in absolute terms on the entire stack it will show the highest contribution.



When examining the contribution to Climate Change impact in electricity stands out as the second major driver. This introduces a potential bias, as the electricity consumption associated with manufacturing at laboratory scale is not optimized and may differ significantly from the allocation expected at industrial scale.

Table 25. Input flow percentage contribution AROC/CROC – Climate Change impact category

Climate change		
Input flow	**CROC**	**AROC**
Materials	67%	51%
Electricity	32%	46%
EoL	1%	3%

3.7.2 Catalysts impact assessment results

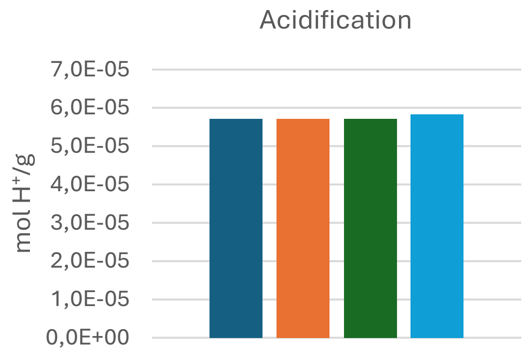
The catalyst load applied in the reactor is different depending on the catalyst material:

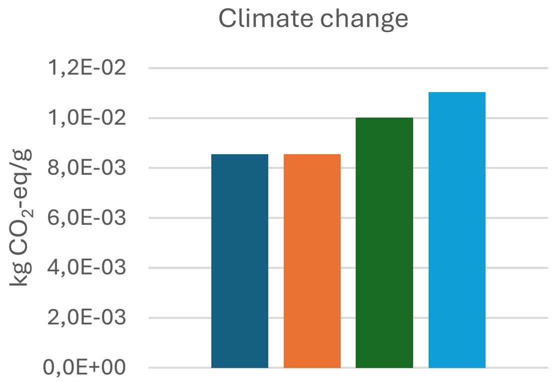
Catalyst option	Catalyst load [mg/cm^2]
MoS_2	2
MoS_2/C	2
NiFe	3,5
NiMo	4

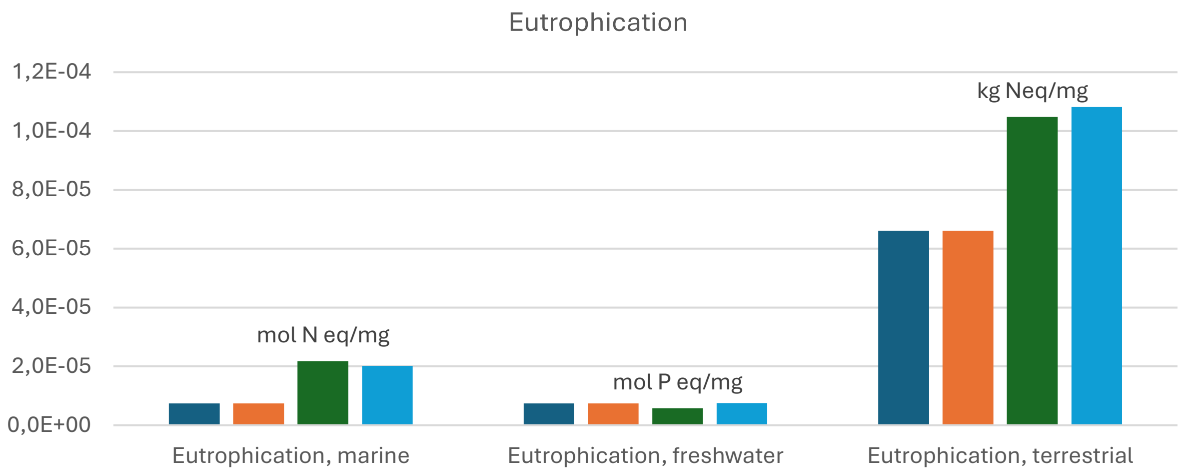
To facilitate comparison among the catalysts options, the results in the following charts refer to their unitary impact (i.e. the reference flow for the results is 1 mg of catalyst).

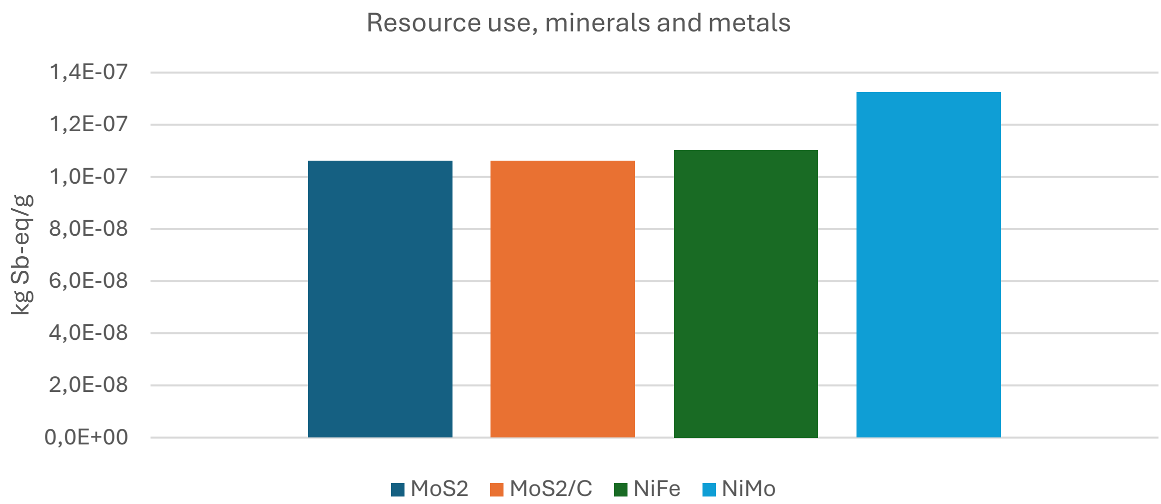
It can be observed that Ni-based catalysts show higher climate change impacts. NiMo based catalyst shows the highest impacts in climate change, eutrophication terrestrial potential and Resource use, minerals and metals impact categories.

Consequently, considering the absolute impacts for the entire REDHy stack, NiMo based catalyst will also show higher absolute emissions in all the categories analyzed due to its higher load. See Appendix C – Results for all the absolute results at REDHy stack level.









When examining the contribution to Climate Change impact in Table 26, electricity stands out as the primary driver, especfially for the catalysts option in which Ni is not present. This introduces a potential bias, as the electricity consumption associated with catalyst manufacturing at laboratory scale is not optimized and may differ significantly from the allocation expected at industrial scale.

Table 26. Input flow percentage contribution – Climate Change impact category

Climate change contribution				
Input flow	**MoS_2**	**MoS_2/C**	**NiFe**	**NiMo**
Materials	17%	17%	49%	36%
Electricity	83%	83%	51%	64%
EoL	0,01%	0,01%	0,01%	0,01%

3.7.3 Electrode impact assessment results

For the electrode only one option is currently tested, therefore the results are reported only in the form of Table 27. These results refer to the overall electrode quantity in the stack (2 electrodes per cell, 25 cm^2 each, for 5 cells).

Table 27. GO electrode LCIA results, for selected impact categories

Impact category	Result
Acidifcation [mol H^+]	3,79
Climate change [kg CO_2-eq]	655,77
Eutrophication, marine [kg N eq]	0,60
Eutrophication, freshwater[kg P eq]	0,62
Eutrophication, terrestrial [mol N eq]	5,30
Resource use, minerals and metals [kg Sb eq]	0,009

Anticipating the results shown in Section 3.7.6, the Climate Change impact category of the electrodes represents 60% of total REDHy cradle-to-gate and EoL impacts.

When examining the contribution to Climate Change impact in Table 28, electricity stands out as the primary driver. This introduces a potential bias, as the electricity consumption associated with electrode manufacturing at laboratory scale is not optimized and may differ significantly from the allocation expected at industrial scale.

Table 28. Input flow percentage contribution – Climate Change impact category

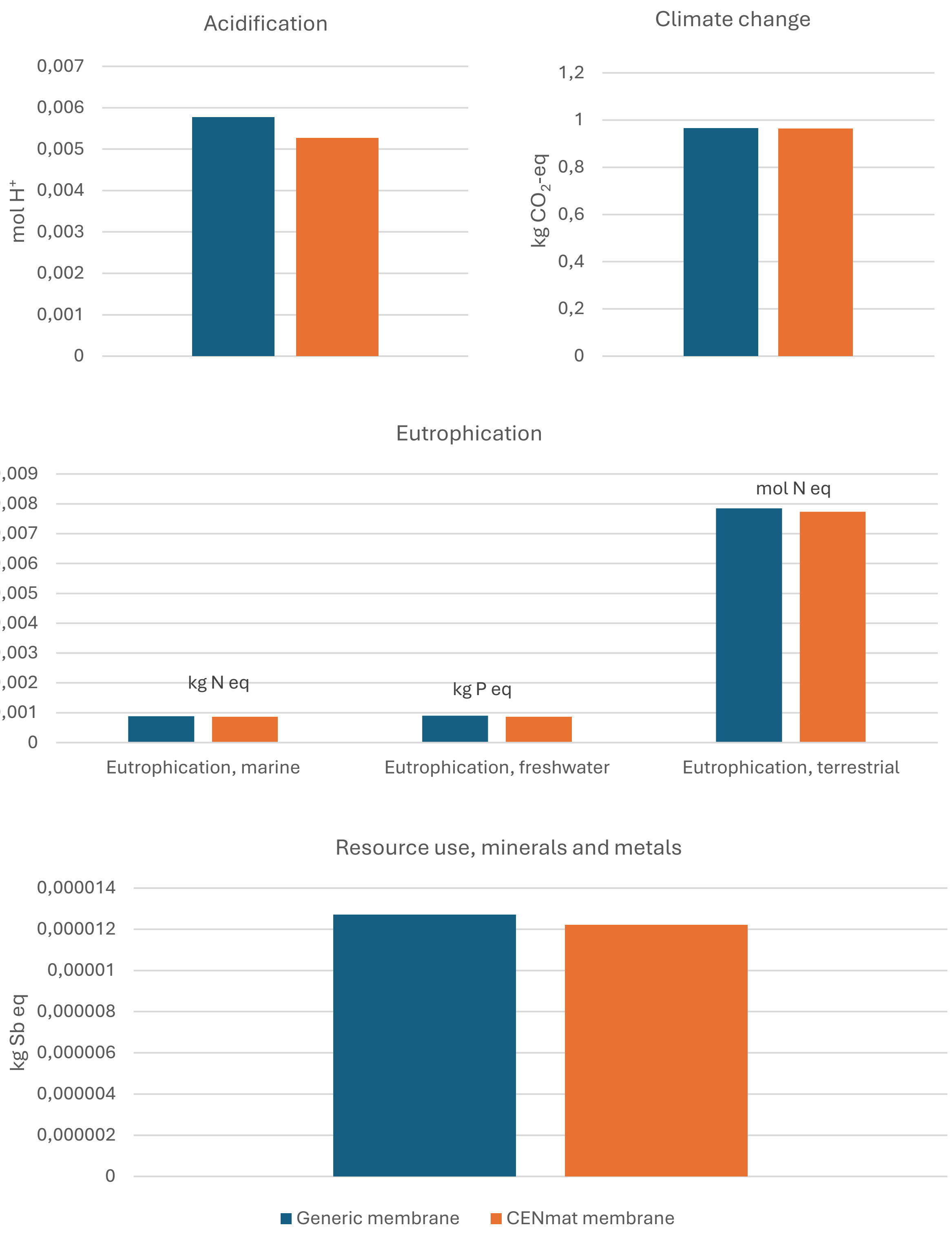
Climate change	
Input flow	**% contribution**
Materials	6%
Electricity	94%
EoL	0,001%

3.7.4 Membrane impact assessment results

Currently, two PFAS-free membrane options have been tested, a commercial membrane and CENmat membrane.

The results are reported considering the total quantities in the REDHy stack (25 cm^2/cell, 5 cells).

CENmat membrane shows almost equal values in all the impact categories reported. In acidification a slightly minor impact is found for CENmat membrane, this is of the different solvents used in the two mebranes.



When examining the contribution to Climate Change impact in Table 29, electricity stands out as the primary driver. This introduces a potential bias, as the electricity consumption associated with membrane manufacturing at laboratory scale is not optimized and may differ significantly from the allocation expected at industrial scale.

Table 29. Input flow percentage contribution membrane – Climate Change impact category

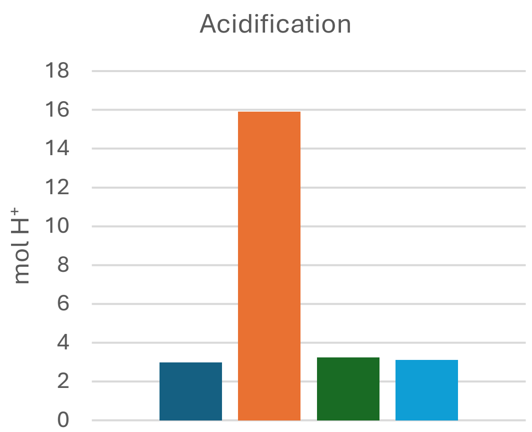
Climate change		
Input flow	**CENmat**	**Other**
Materials	10%	3%
Electricity	89%	95%
EoL	1%	1%

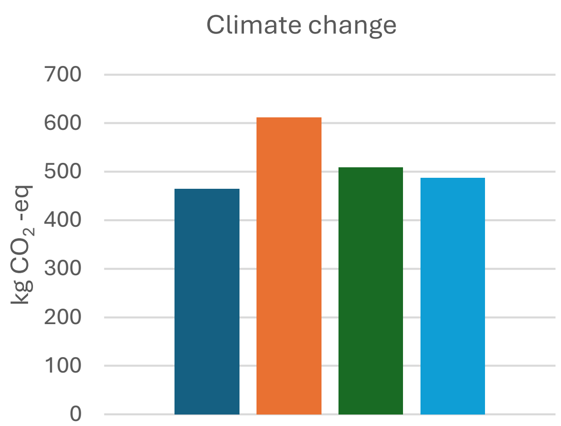
3.7.5 Stack and BoP impact assessment results

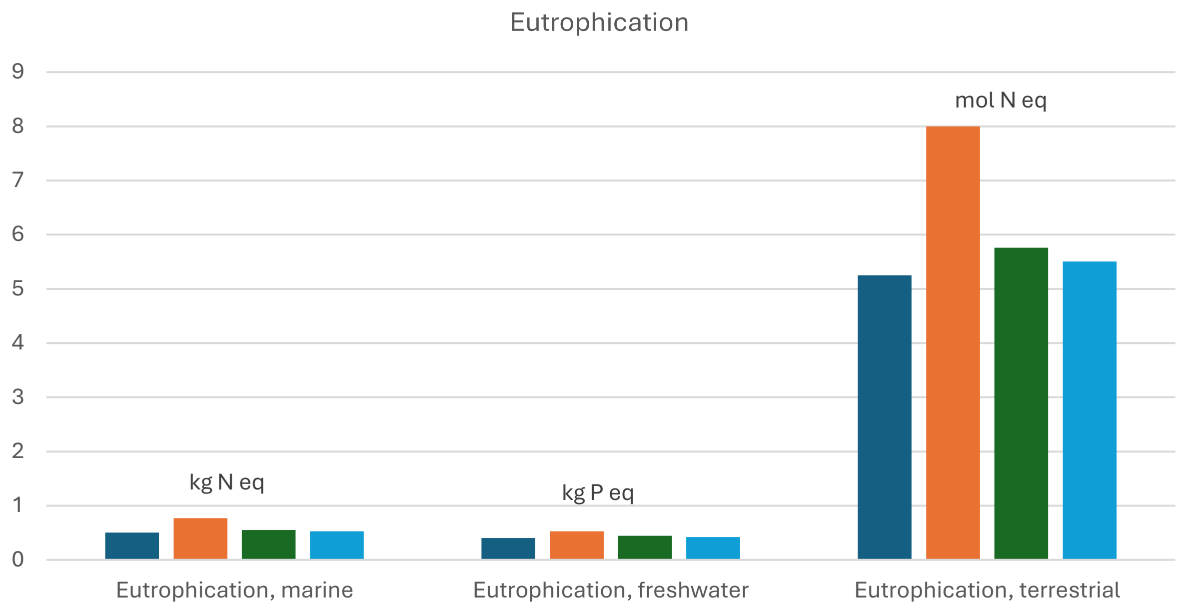
Four different scenarios are analyzed, depending on the BPPs material composition. The results are reported considering the overall quantities of the REDHy system.

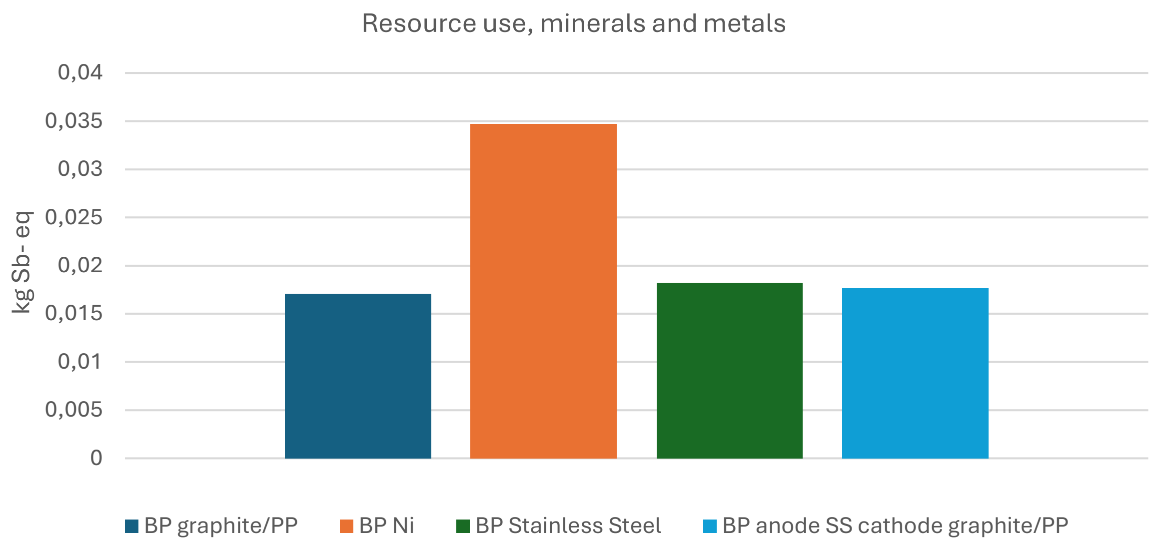
The Ni option shows the highest impacts in all the highlighted impact categories. All the other options are comparable among them in terms of environmental impacts for the selected impact categories.

All the detailed results are reported in Appendix C – Results.









In this case the breakdown by input flow cannot highlight the electricity contribution because the manufacturing of these components is not within WP6 project scope, but they will be supplied by external vendors. Therefore, to account for the manufacturing generic datasets have been considered.

For the Climate Change category, the breakdown is reported clustering the impacts for the stack and the BoP. The BoP contribution is only 1%.

Nevertheless, there is the risk that this share is underestimated because currently only partial designing of the BoP has been concluded. For example, electronics and electrical components (which generally have a high impact in terms of greenhouse gases emissions) are currently not defined.

Table 30. Input flow percentage contribution stack and BoP – Climate Change impact category

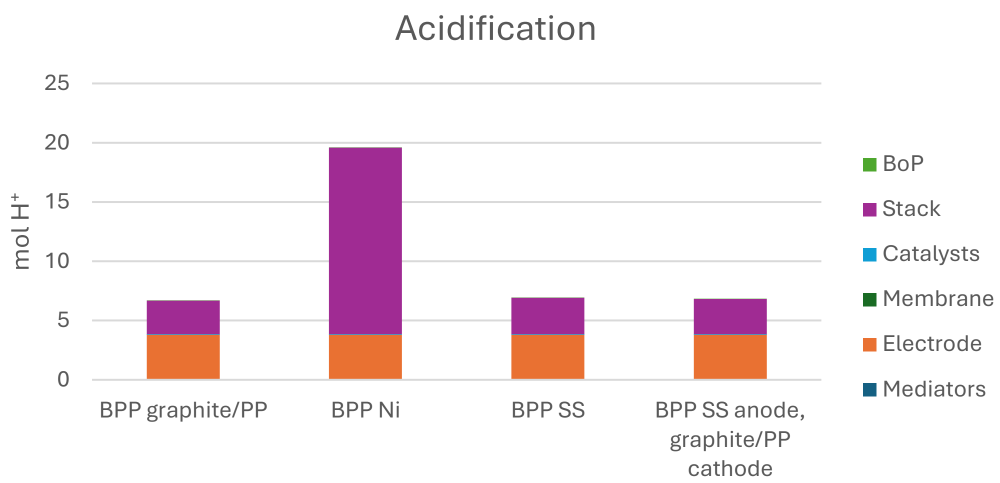
Climate change				
Input flow	**BPP graphite/PP**	**BPP Ni**	**BPP Stainless Steel**	**BPP anode SS cathode graphite/PP**
Stack	93%	94%	93%	93%
BoP	1%	1%	1%	1%
EoL	6%	5%	6%	6%

3.7.6 Cradle-to-gate impact assessment results

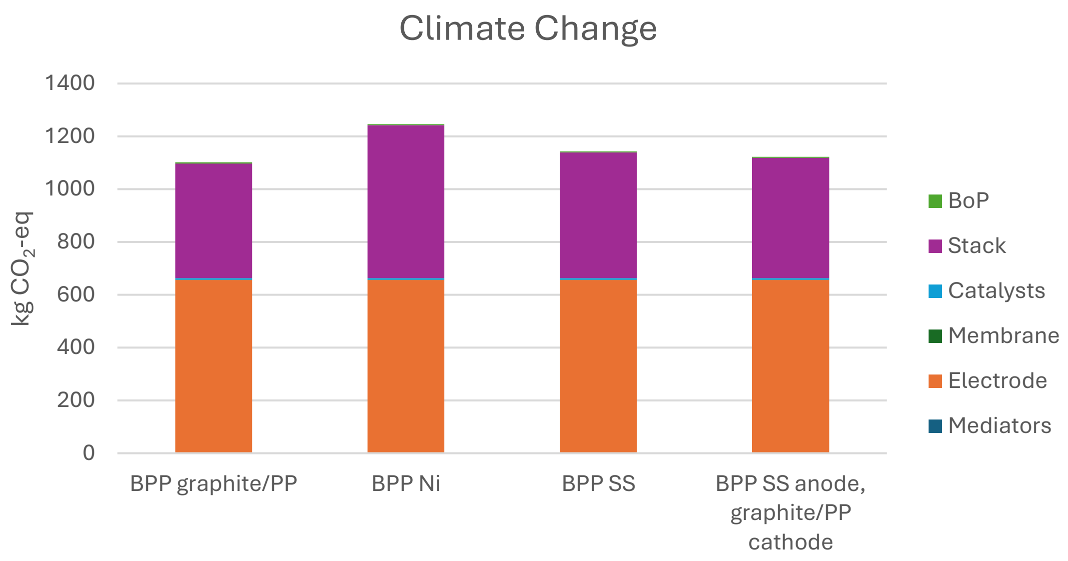
Cradle-to-gate system boundaries refers to only life cycle phases related to product construction (Raw material extraction – Materials processing – Manufacturing).

In this Section the results shown in the previous chapters for each component are shown together, to compose the REDHy system. The charts are related to 4 different options, depending on the BPPs material. The other components are fixed (the selected options are MoS_2/C and NiFe catalysts and CENmat membrane).

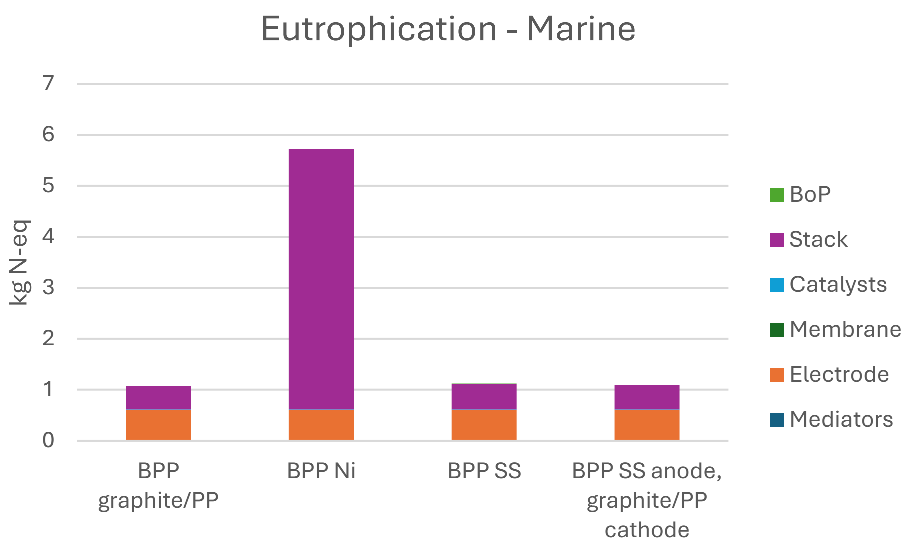
The results for all 27 impact categories are shown in Appendix C – Results. The results for the 27 impact categories are reported at component level, i.e. together with their related EoL impacts.



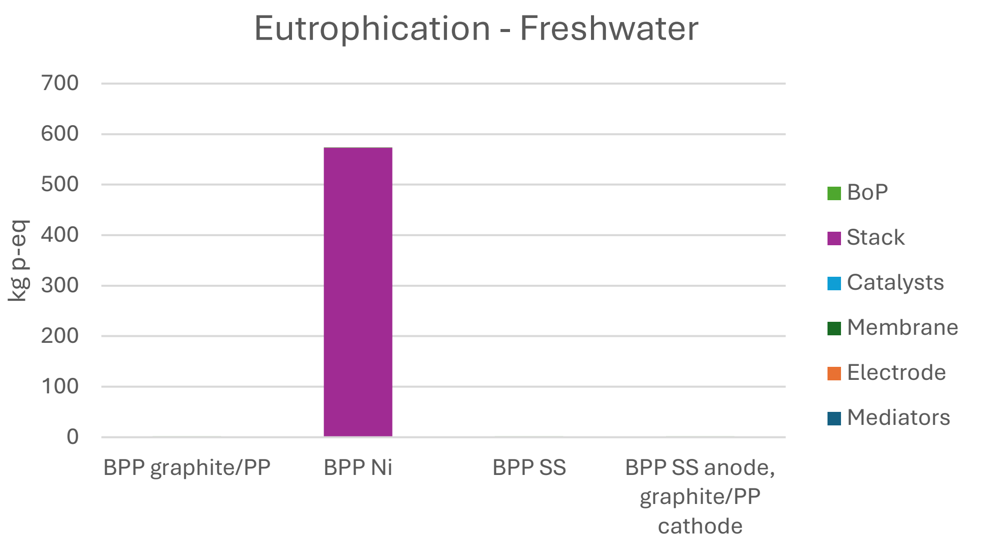
Within the Acidification impact category, electrodes represent the main contributor (>50%), except in the scenario where BPPs are made of nickel (in this case electrodes contribution is only 19%). In that case, the stack becomes the dominant driver. Moreover, this option results in higher overall impacts compared to all other configurations (about 20 mol H^+ instead of 6,7-6,9 mol H^+).



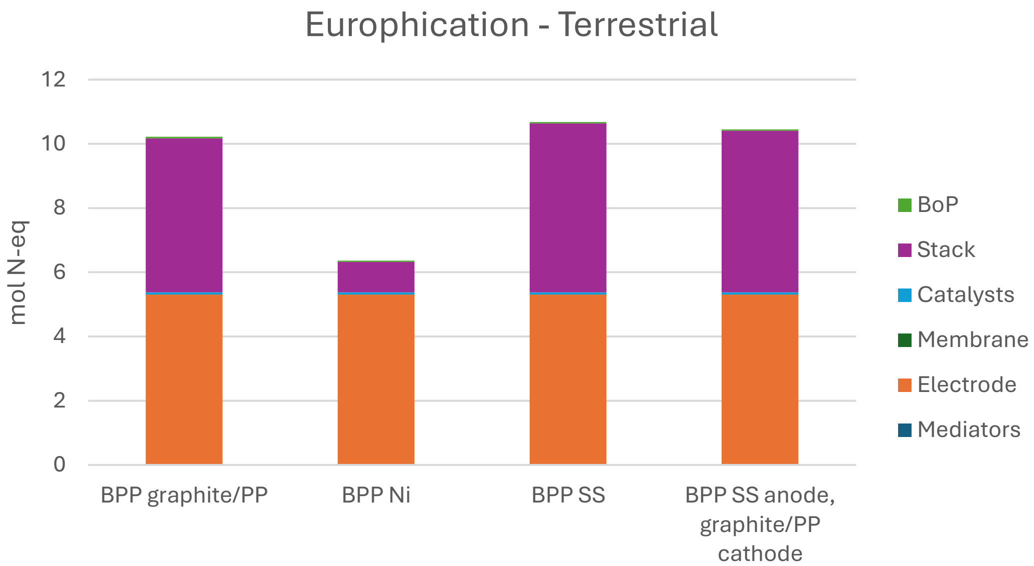
In Climate change impact category, the highest impacts come from the electrodes (accounting for 53-60%), followed by the stack. However, it should be considered that the electricity consumption jeopardizes the electrodes results (being responsible for 94% of its total impact) and that BoP components currently modelled are only partially representative of the overall REDHy system BoP because design is still under development.



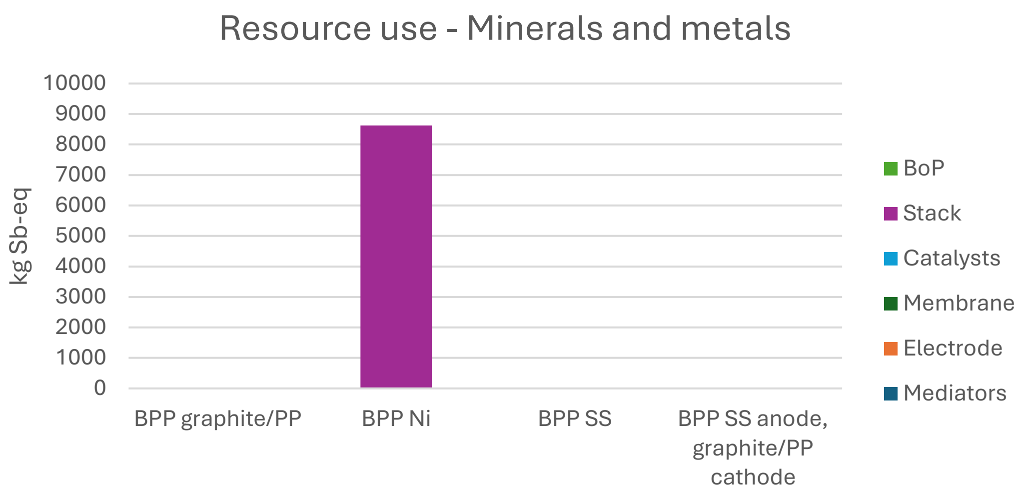
In Eutrophication – Marine impact category similar considerations as for Acidification impact category are found.



In the case of Eutrophication – Freshwater the impacts of most of the options are negligible when compared to the option in which BPP is made of Ni. As can be seen, in this case the Stack is the only contributor to the overall impact (>99,8%).



In Eutrophication – Terrestrial impact category, the electrodes constitute the main contribution, followed by the Stack. Only 1% of the total impacts is due to the catalysts across all the options.



In the Resource Use, minerals and metals impact category, the highest contribution is due to the Stack. Additionally, the solution in which BPP are made of Ni has almost two orders of magnitude higher impact than the other configurations.

3.7.6.1 Comparison with SoA

With respect to the benchmarking review (see Section 2.2) the figure below shows the cradle-to-gate results of the REDHy system:

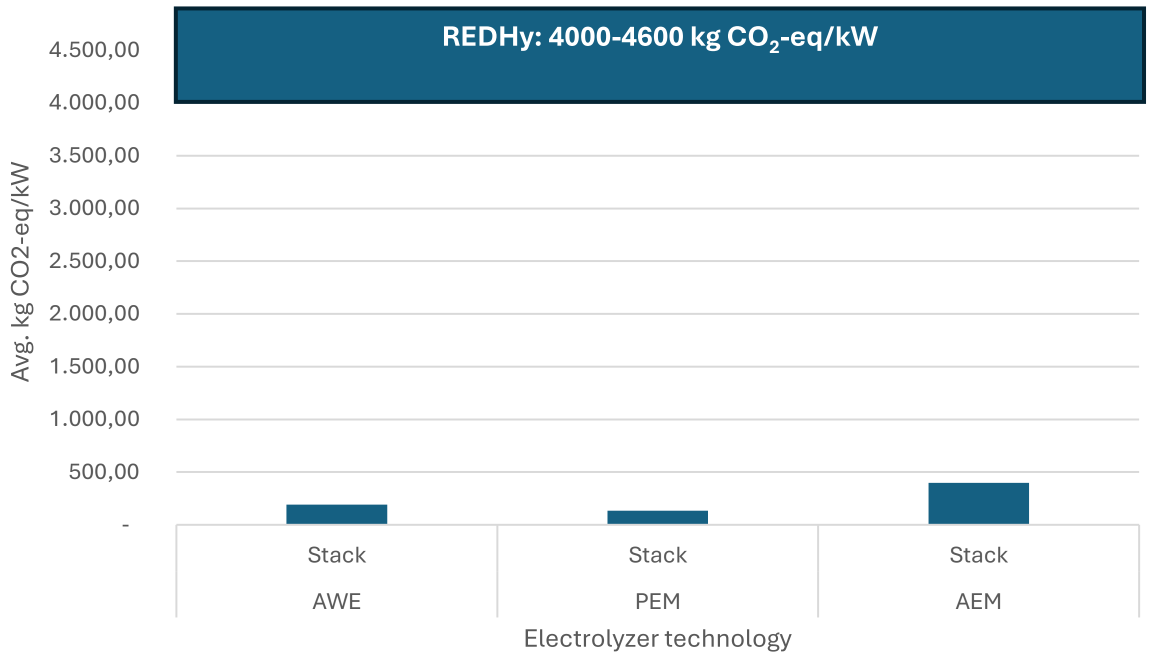


Figure 14. Cradle-to-gate impact assessment results comparison with SoA technologies

It can be noted that at current project status the REDHy system is showing much higher impacts in relation to Climate Change impact category. This is mainly due to:

- Electricity not optimized at lab-scale manufacturing processes

- Unreached target capacity of the REDHy system at the time of this deliverable (being the target equal to 1,5 kW)

3.7.7 Transport to end user impact assessment results

In Table 31 the transportation LCA results are shown for the highlighted impact categories, by kg H_2 produced. See Appendix C – Results for the results of all the 27 impact categories.

Table 31. Transport to end user LCIA results

Acidification [mol H^+/kg H_2]	Climate change [kg CO_2-eq/kg H_2]	Eutrophication, marine [kg N-eq/kg H_2]	Eutrophication, freshwater [kg p eq/kg H_2]	Eutrophication, terrestrial [mol N-eq/kg H_2]	Resource use, minerals and metals [kg Sb-eq/kg H_2]
0,021	5,408	0,007	0,0004	0,081	0,00003

3.7.8 Use phase impact assessment results

In Table 32 the results for the use phase input flows are reported for the most relevant impact categories as stated in the FC-HyGuide. For each impact category the results are expressed in terms of kg H2 produced.

The highest contribution to each impact category is related to electricity consumption, considering an average between solar energy and wind energy.

Table 32. LCIA for the use phase

Impact category	Energy consumption, solar and wind average	Wastewater, avg	KOH	Ultrapure water, as feedstock
Acidification [mol H^+/kg H_2]	2,18E-02	3,4E-07	1,4E-04	1,0E-04
Climate change [kg CO_2-eq/kg H_2]	3,42E+00	7,0E-05	2,6E-02	2,2E-02
Eutrophication, marine [mol N-eq/kg H_2]	3,83E-03	2,9E-06	2,9E-05	2,1E-04
Eutrophication, freshwater [kg P-eq/kg H_2]	1,79E-03	3,2E-07	1,1E-05	4,2E-04
Eutrophication, terrestrial	4,02E-02	1,1E-06	2,9E-04	1,7E-04

[mol N-eq/kg H_2]				
Resource use, minerals and metals [kg Sb-eq/kg H_2]	1,35E-04	3,5E-10	2,6E-07	6,5E-08

3.7.9 EoL impact assessment results

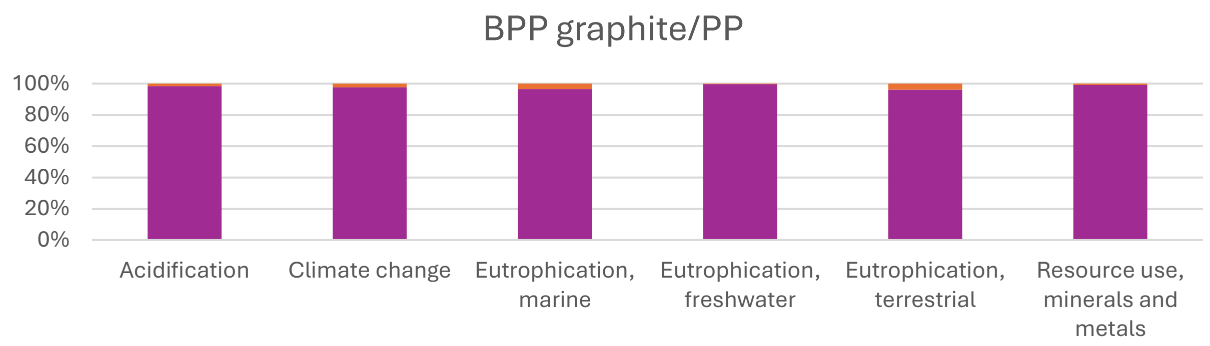
End-of-Life refers to product transportation to the disposal site and its disposal treatment. The current results are based on the disposal scenarios communicated by project partners.

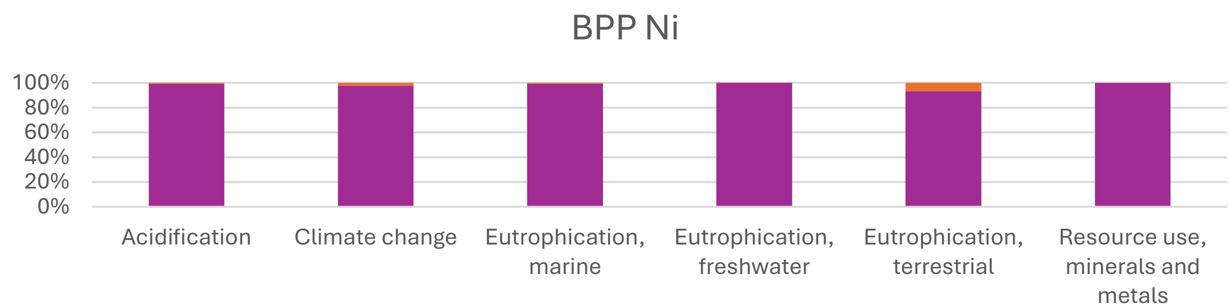
In this Section the results are shown when summing together each component that composes the REDHy system. For all the 4 different BPPs options the main driver contributing to EoL impacts across all the impact categories is the Stack+BoP (>99%). This is linked to the fact that:

- The Stack and BoP constitute the heaviest mass of the REDHy system
- For plastics not considered as recyclable, waste incineration has been selected

The results for all 27 impact categories are shown in Appendix C – Results. The results are shown together with cradle-to-gate impacts.

Anyway, when considering cradle-to-gate results plus EoL results (see the figures below), the percentage contribution of EoL is always less than 4% in all BPP options and impact categories.





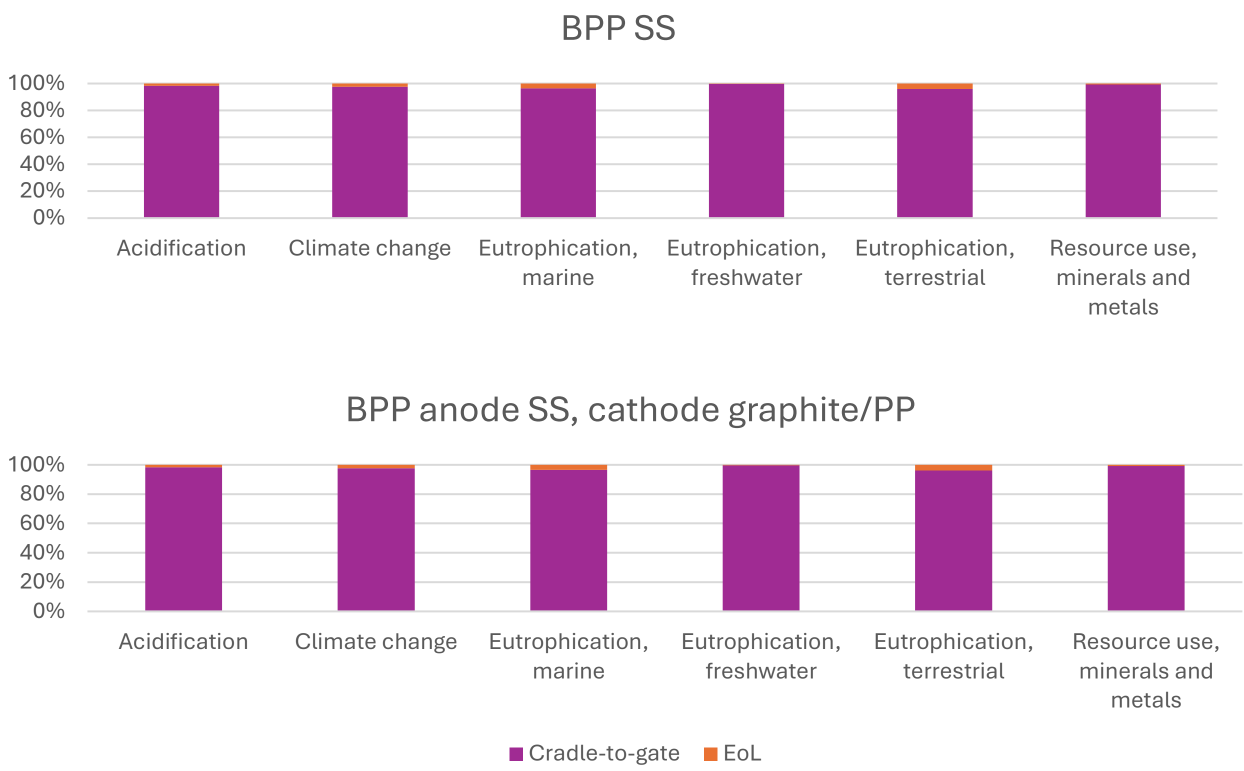


Figure 15. Cradle-to-gate and EoL impact assessment contribution

3.7.10 Cradle-to-grave impact assessment results

In this Section, the overall REDHy impacts by functional unit (1 kg H_2) are reported. The contribution of each life cycle phase to the total results is shown.

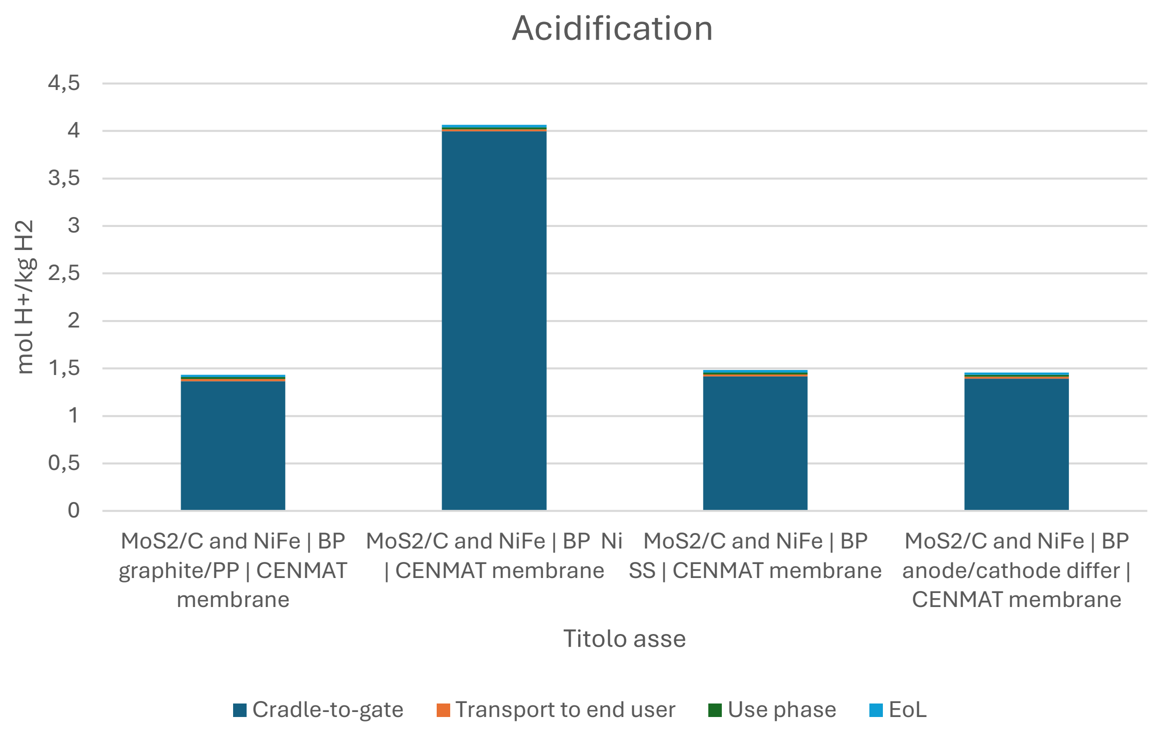


Figure 16. Cradle-to-grave impact assessment results - Acidification

The cradle-to-gate impacts contribute to 95-98% of total Acidification impacts of the REDHy system. The EoL and Use phases are contributing to 2% each, while the transport to end user represents only 1% of the impacts.

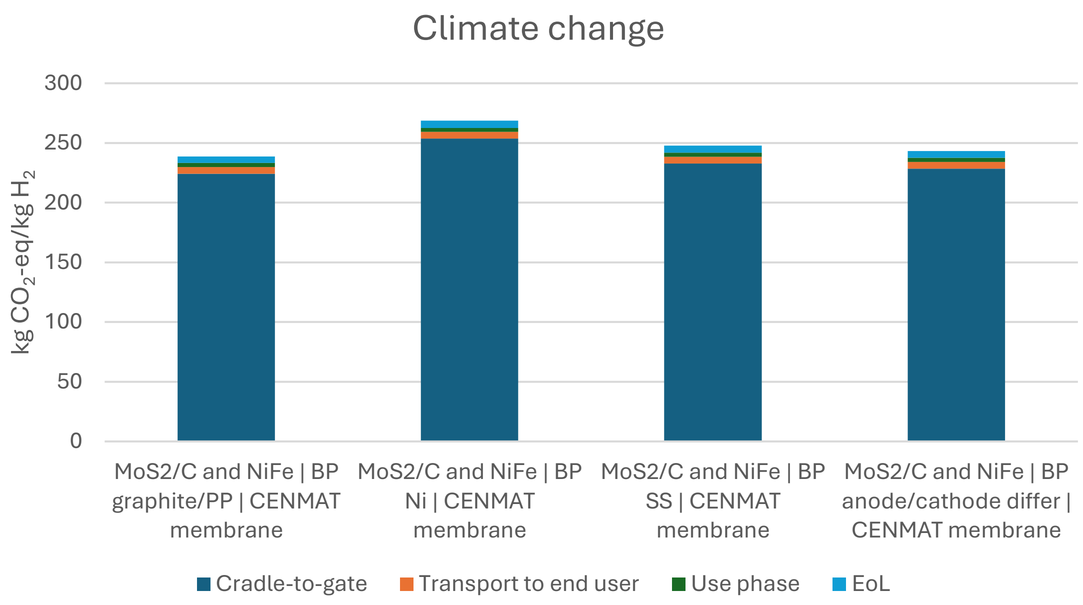


Figure 17. Cradle-to-grave impact assessment results – Climate Change

In Climate Change impact category, the main contribution comes from the cradle-to-gate life cycle phase (94%). Transport to end user and EoL accounts both for 2% while Use phase accounts for only 1,3-1,5% of total Climate Change results.

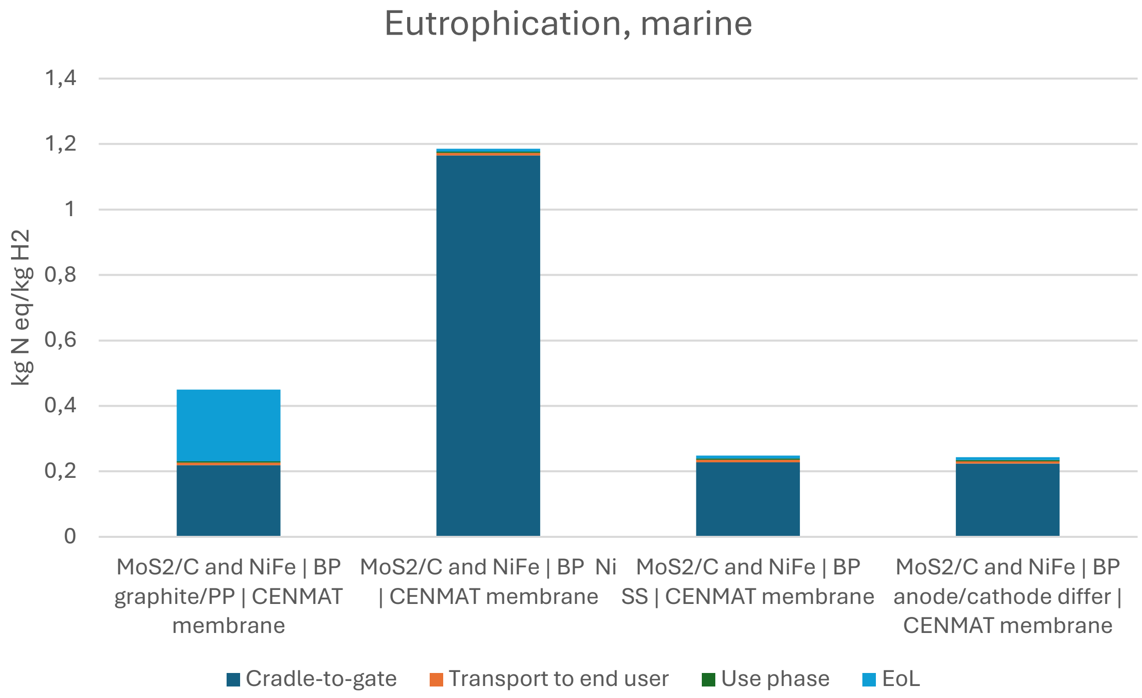


Figure 18. Cradle-to-grave impact assessment results – Eutrophication, marine

Cradle-to-gate life cycle phase shows the highest contribution (>90%) in all the options analyzed, except for the configuration in which BPPs are made of graphite/PP, in which it is just 50% of the total impact and the other half is due to EoL.

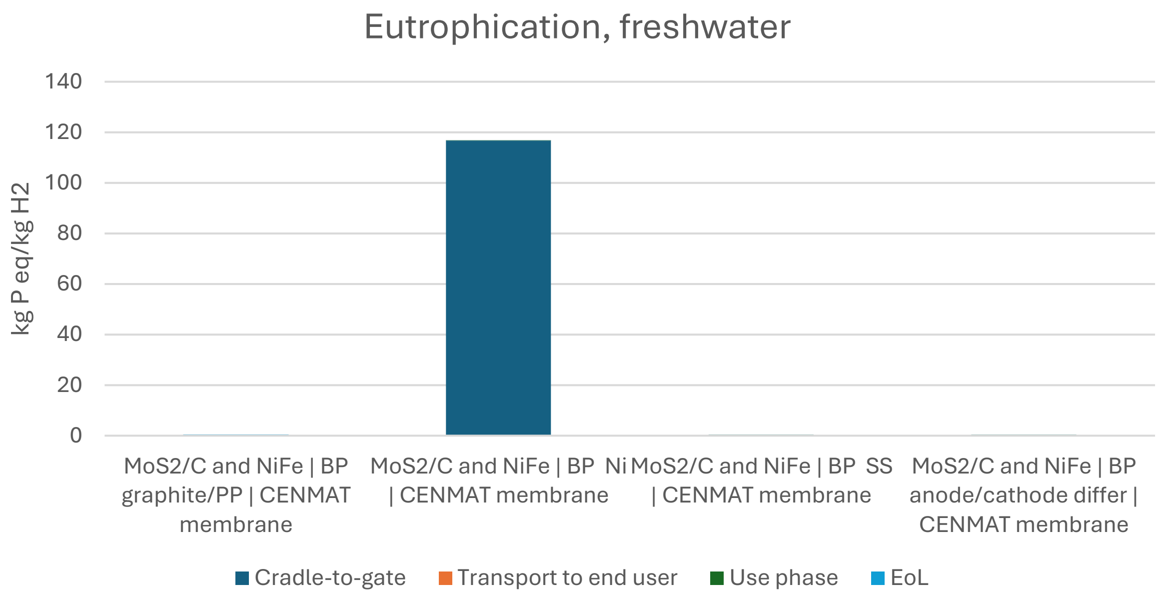


Figure 19. Cradle-to-grave impact assessment results – Eutrophication, freshwater

Cradle-to-gate life cycle phase shows the highest contribution (>98%) in all the options analyzed, except for the configuration in which BPPs are made of graphite/PP, in which it is just 50% of the total impact and the other half is due to EoL. Additionally, the option in which BPPs are made of Ni has one order of magnitude higher overall Eutrophication, freshwater impact than all the other options.

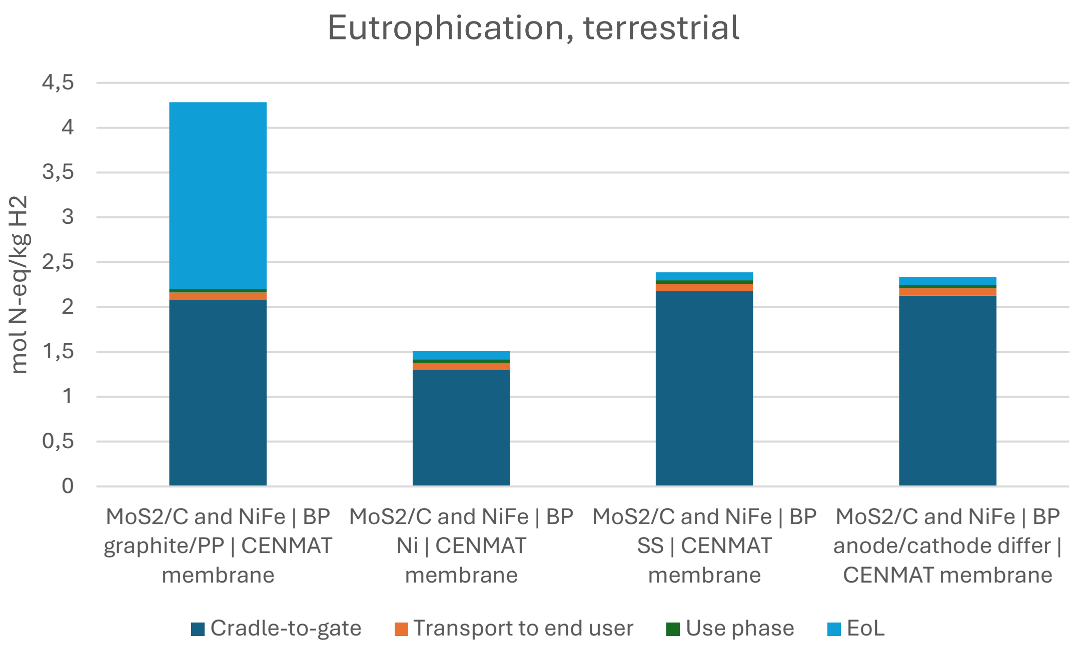


Figure 20. Cradle-to-grave impact assessment results – Eutrophication, terrestrial

Cradle-to-gate life cycle phase shows the highest contribution (around 90%) in all the options analyzed, except for the configuration in which BPPs are made of graphite/PP, in which it is just 50% of the total impact and the other half is due to EoL. Additionally, this option shows also double overall Eutrophication, terrestrial impacts with respect to all the other BPPs configurations.

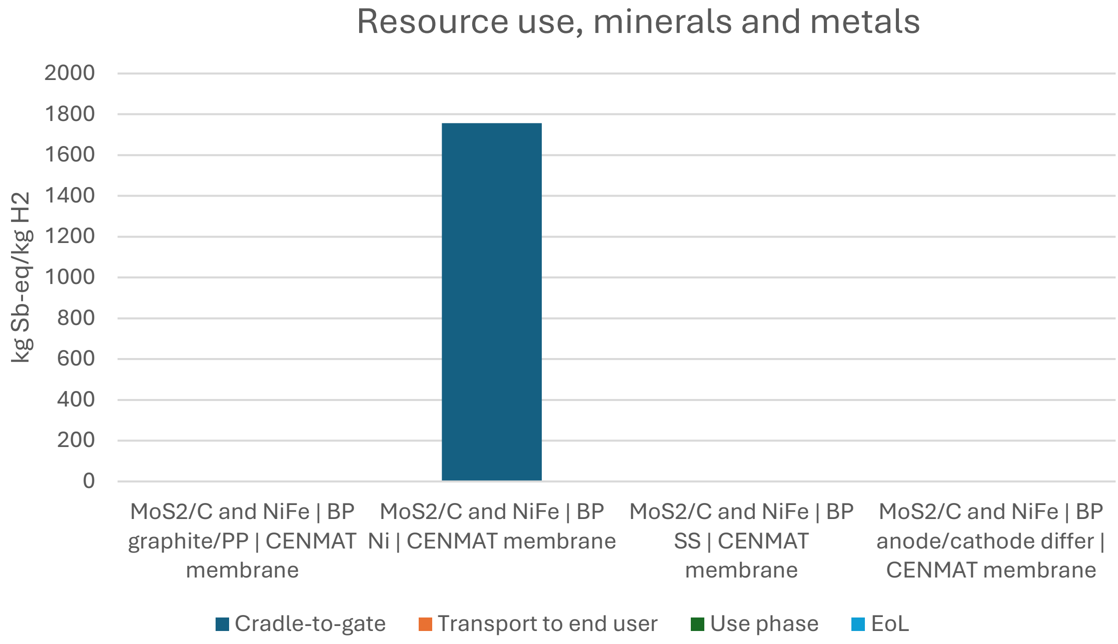


Figure 21. Cradle-to-grave impact assessment results – Resource use, minerals and metals

Cradle-to-gate life cycle phase shows the highest contribution (>96%) in all the options analyzed. Additionally, the option in which BPPs are made of Ni has two order of magnitude higher overall impact than all the other options.

3.8 Life Cycle Assessment interpretation

3.8.1 Limitations of the study

Regarding the cradle-to-gate impact assessment results the main limitation is related to the high consumptions of the manufacturing processes, since they are performed at lab scale. This causes a risk of jeopardizing the results of almost all the components falling within the REDHy system.

Furthermore, some components of the stack and/or the BoP are still under investigation, therefore the final REDHy system components configuration is not defined yet. Currently the higher risk is represented by a limited amount of BoP components modelled. In addition to this, in the LCA model the AROC load considered refers to a commercial AROC and not specifically to AC6 that has been developed by UPV, because as of now AC6 has not been tested.

At present, the assessment of waste generated during component manufacturing has only been partially addressed, primarily using generic datasets for stack and BoP production. A more detailed evaluation of output flows should be included in future analyses. Given that this is a preliminary study and multiple material options are still under investigation, this deliverable focuses exclusively on input flows for the current stage.

Regarding the End-of Life, recycling has been considered for different components made of plastics. Nevertheless, further assessment of these scenarios should be performed in the context of the circularity assessment accounting for the actual practices and statics of plastic recycling instead of theoretical considerations.

Regarding the use phase, currently the only performance data available refers to a single cell of 5 cm2. Therefore, performances have been inferred to compute the impacts for a stack made of 5 cells of 25 cm^2 each. Furthermore, target data have been considered to model electrode degradation and lifetime of the REDHy system.

Additionally, maintenance-related energy and material consumptions have not been included due to the lack of data from degradation tests, which have not yet commenced at the current stage of the project.

3.8.2 Improvements for the study

This chapter provides a summary of potential areas for future improvement. Most of these enhancements are closely tied to advancements in the development of the REDHy system, which are expected to deliver a higher level of data quality.

- **Investigate the output material flows.** In alignment with the REDHy project attention to the environmental impacts of hydrogen production, a detailed focus should be placed on the emissions and wastes generated also during the manufacturing of the electrolyzer itself. At the time of this deliverable, different materials options were still under consideration, therefore, the effort was put only into collecting LCI data of the different input flows for each available option. As improvement for the next deliverables, WP7 will ask project partners to share data also about the output flows.

- **Collect comprehensive data for REDHy performance.** Following the development of the project, actual data for degradation and durability should be implemented in the LCA model. Furthermore, data should be retrieved from full stack tests, not only for single cell.
- **Furhter assessment of EoL scenarios.** Currently the scenarios provided in relation to the EoL are based on theoretical assumptions. Anyway, considering the circularity assessment that is due by the end of the project, further assessment of currently adopted practices should be considered.

4. Conclusion and Recommendation

Finally, in this chapter a summary of the key findings is reported together with recommendations for improvement.

The cradle-to-gate impact assessment indicates that the most significant contributors are the stack and the electrodes. Anyway, REDHy cradle-to-gate LCA is jeopardized by high relevance of electricity consumption associated with the manufacturing phase due to lack of process optimization at lab level. For next analysis, this could be addressed by a specific assessment of the technology up-scale at an industrially relevant scale.

Furthermore, Ni based options resulted in having higher impacts, across all the prioritized impact categories. Furthermore, we highlight that nickel is also listed as Strategic Raw Material within the Critical Raw material Act (UE) 2024/1252.

Currently, the cradle-to-gate life cycle phase has the highest contribution to the overall cradle-to-grave LCA. Anyway, the relevance of the use phase will increase with increased operational lifetime and capacity of the REDHy system.

The End-of-Life phase is not considered significant under the current treatment assumptions. However, we recommend conducting further assessments in future analyses, considering the most up-to-date waste collection rates and the actual disposal treatments applied to these materials.

5. Risks and interconnections

We don't foresee any additional risk or interconnection with respect to what already expressed in the Grant Agreement.

5.1 Risks/problems encountered

Risk No.	**What is the risk**	**Probability of risk occurrence**[1]	**Effect of risk**[1]	**Solutions to overcome the risk**
WP7	TRL project is low, therefore LCA and TEA conclusions may not be representative for the REDHy technology, when compared to high-TRL applications.	2	Driving the development to less optimal targets.	Uncertainty due to low TRL will be reduced by a specific assessment of the technology up-scale at an industrially relevant scale.

1) Probability risk will occur: 1 = high, 2 = medium, 3 = Low

5.2 Interconnections with other deliverables

We do not see any direct interconnection with other partners' deliverables. Interconnections are found only considering upstream sources of info.

6. References

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Project partners:

#	Partner short name	Partner Full Name
1	DLR	DEUTSCHES ZENTRUM FUR LUFT – UND RAUMFARHT EV
2	CNRS	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIC
3	UNR	UNIRESEARCH BV
4	UPV	UNIVERSITAT POLITECNICA DE VALANCIA
5	IDN	INDUSTRIE DE NORA SPA-IDN
6	CENMAT	CUTTING-EDGE NANOMATERIALS CENMAT UG HAFTUNGSBESCHRANKT
7	CNR	CONSIGLIO NAZIONALE DELLE RICERCHE

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Appendix A – Literature studies

Year	1st Author	Paper title
2025	Hoppe	Article Reducing Environmental Impacts of Water Electrolysis Systems by Reuse and Recycling: Life Cycle Assessment of a 5 MW Alkaline Water Electrolysis Plant
2025	Driemer	Electrolytic hydrogen in a large-scale decarbonized grid with energy reservoirs: An assessment of carbon intensity and integrity
2025	Dincer	Sustainability analysis of electrolysis based green hydrogen production pathways: A life cycle perspective
2024	Moranti	Environmental performance of a metal-supported protonic ceramic cell and an electrolyte-supported solid oxide cell for steam electrolysis
2024	Ajeeb	Life cycle analysis of hydrogen production by different alkaline electrolyser technologies sourced with renewable energy
2024	Wei	Comparative life cycle analysis of electrolyzer technologies for hydrogen production: Manufacturing and operations
2024	Ortiz	Environmental Assessment of Liquid Hydrogen Production Routes
2024	Sial	Techno-economic Analysis and Life Cycle Assessment of Green Hydrogen Production: A Case Study of Sur Industrial City in Oman
2024	Patel	Climate change performance of hydrogen production based on life cycle assessment
2024	Krishnan	Prospective LCA of alkaline and PEM electrolyser systems
2024	Koj	Life cycle environmental impacts and costs of water electrolysis technologies for green hydrogen production in the future
2024	Koj	Green hydrogen production by PEM water electrolysis up to the year 2050
2024	Hemmati	Life-Cycle Assessment of Renewable-based Hydrogen Production via PEM Electrolyzer in Indonesia
2024	Gerhardt-Morsdorf	Life Cycle Assessment of a 5 MW Polymer Exchange Membrane Water Electrolysis Plant
2024	Schropp	Environmental and material criticality assessment of hydrogen production via anion exchange membrane electrolysis
2023	Pawlowski	Is the Polish Solar-to-Hydrogen Pathway Green? A Carbon Footprint of AEM Electrolysis Hydrogen Based on an LCA
2023	Riemer	Environmental implications of reducing the platinum group metal loading in fuel cells and electrolysers: Anion exchange membrane versus proton exchange membrane cells

2023	Sollai	Renewable methanol production from green H2 and captured CO2: technoeconomic assessment
2023	Cho	A review on global warming potential, challenges, and opportunities of renewable hydrogen production technologies
2023	Hren	Hydrogen production, storage and transport for renewable energy and chemicals: an environmental footprint assessment
2023	Lubecki	A comparative environmenta l LCA study of hydrogen fuel, electricity and diesel fuel for public buses
2022	Zhang	LCA of three types of H2 production methods using solar energy
2022	Wulf	Analyzing the future potential of defosslizing industrial specialty glass production with hydrogen by LCA
2022	Terlouw	Large -scale hydrogen production via water electrolysis: a techno - economic and environmental assessment
2022	Schropp	Prospective LCA: case study of H 2 production via water electrolysis
2021	Palmer	Life -cycle greenhouse gas emissions and net energy assessment of large -scale hydrogen production via electrolysis and solar PV
2021	Lotric	LCA of hydrogen technologies with the focus on EU critical raw materials and EoL strategies
2021	Lee	ntegrative techno - economic and environmenta l assessment for green H2 production by alkaline water electrolysis based on experimental data
2021	Gerloff	Comparative LCA analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production
2021	Delpierre	Assessing the environmenta l impacts of wind -based hydrogen production in the Netherlands using ex -ante LCA and scenarios analysis
2021	Al-Qahtani	Uncovering the true cost of hydrogen production routes using life cycle monetization
2020	Zhao	LCA of H 2O electrolysis technologies
2020	Valente	Prospective carbon footprint comparison of H 2 option s
2020	Valente	Using harmonized life cycle indicators to explore the role of H 2 in the environmental performance of fuel cell electric vehicles\
2020	Sadeghi	Comparative economic and LCA of solar - based H 2 production for oil and gas industries
2019	Stropnik	Critical materials in PEMFC systems and LCA analysis for potential reduction of environmental impacts with EoL strategies
2019	Ely4off	PEM ElectroLYsers FOR operation with OFFgrid renewable facilities
2019	Bareiss	Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems
2018	Valente	Harmonizing methodologic al choices in life cycle assessment of hydrogen: A focus on acidification and renewable hydrogen

2018	Wulf	Hydrogen supply chains for mobility - environmental and economic assessment
2018	Rivera	Environment al sustainability of renewable hydrogen in comparison with conventional cooking fuels
2018	Mehmeti	LCA and Water Footprint of H2 production
2017	Koj	Site - Dependent Environment al Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis
2017	Zhang	Life Cycle Assessment of Power -to - Gas: Approaches, system variations and their environmental implications
2016	Ghandehariun	Life cycle assessment of wind -based hydrogen production in Western Canada
2016	Burkhard t	Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply
2015	Topriska	Solar hydrogen system for cooking applications: Experimental and numerical study
2015	Koj	Life Cycle Assessment of improved high pressure alkaline electrolysis
2014	Bhandari	Life cycle assessment of hydrogen production via electrolysis - a review
2013	Wulf	LCA of bio H2 production as a transportation fuel in Germany
2013	Patyk	LCA of H 2 generation with high temperature electrolysis
2010	Staffell	LCA of an alkaline fuel cell CHP system

Appendix B - LCI

Table 33. LCI for Stack components

Item	Dataset	Value [kg]
Reference flow: 1 pc of item		
Bipolar plate, graphite/PP	Synthetic graphite, battery grade {RoW}| market for synthetic graphite, battery grade | Cut-off, S – assumed 10% of BP total weight[12]	0,146*0,01
	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, S – assumed 90% of total weight	0,146*0,9
	Compression of sheet moulding compound {GLO}| market for compression of sheet moulding compound | Cut-off, S[13]	0,146
Bipolar plate, Nickel	Nickel, class 1 {GLO}| market for nickel, class 1 | Cut-off, S	0,664
	Sheet rolling, nickel, RER	
	nickel working, average for nickel product manufacturing, RER	
Bipolar plate, Stainless steel	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	0,597
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Endplate	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	2,14
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Reactor	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	2,671+3,379[14]
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Tank	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	1,681+3,016[16]
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	

[12] Reason of assumption: graphite is a "blend" according to supplier datasheet.
[13] This manufacturing process is considered based on the supplier datasheet.
[14] Sum of the body and flange weights, respectively.

	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Housing	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	8,942+3,067
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Electrolyte distributor	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	1,818
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Tubes, 6 mm diameter	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, S	0,003
	Injection moulding {GLO}| market for injection moulding | Cut-off, S	
Tubes, 14 mm diameter	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, S	0,013
	Injection moulding {GLO}| market for injection moulding | Cut-off, S	
Swagelok SS-6M0-1-2RT	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	0,022
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Swagelok SS-14M0-1-8RS	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	0,14
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
Stack fixing edge	Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, S	0,247
	Sheet rolling, chromium steel {GLO}| market for sheet rolling, chromium steel | Cut-off, S	
	Metal working, average for chromium steel product manufacturing {GLO}| market for metal working, average for chromium steel product manufacturing | Cut-off, S	
	Copper, cathode {GLO}| market for copper, cathode | Cut-off, S	0,442

Connector current supply	Sheet rolling, copper {GLO}| market for sheet rolling, copper | Cut-off, S	
	Metal working, average for copper product manufacturing {GLO}| market for metal working, average for copper product manufacturing | Cut-off, S	
Calorplast heat exchanger	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, S	3,24
	Injection moulding {GLO}| market for injection moulding | Cut-off, S	
Gasket	PVDF polymer[15]	0,005
	Injection moulding {GLO}| market for injection moulding | Cut-off, S	
Insulation panel	Polysulfone {GLO}| market for polysulfone | Cut-off, S	0,037
	Injection moulding {GLO}| market for injection moulding | Cut-off, S	

[15] Ad hoc dataset. Modelled according to 2022 - Hu - *Life Cycle Assessment of the Polyvinylidene Fluoride Polymer with Applications in Various Emerging Technologies* (link here) – Selected Route 1) for LCI data as it is considered most common production route for PVDF.

Table 34. LCI for BoP system

Item	Dataset	Weight [kg/pc]	Amount [pc]
Swagelok SS-14M0-1-8RS	See Table 33		1
Swagelok SS-12M0-3-8TTM	Same datasets used for Swagelok SS-14M0-1-8RS in Table 33	0,15	1
Swagelok SS-6M0-1-4W		0,05	1
Swagelok SS-10M0-1-8W		0,1	2

Appendix C – Results

Table 35. WP2 cradle-to-gate+EoL impact assessment results (reference flow: 1 REDHy system) – Redox mediators

Impact category	CROC		AROC	
	Ref flow: 1 REDHy system	Ref flow: Functional unit (1 kg H_2)	Ref flow: 1 REDHy system	Ref flow: Functional unit (1 kg H_2)
Acidification	0,000269501	5,48837E-05	7,84E-05	1,6E-05
Climate change	0,049133413	0,01000599	0,017727	0,00361
Climate change - Biogenic	4,29364E-05	8,74397E-06	2,05E-05	4,18E-06
Climate change - Fossil	0,049035722	0,009986095	0,017679	0,0036
Climate change - Land use and LU change	5,47544E-05	1,11507E-05	2,74E-05	5,58E-06
Ecotoxicity, freshwater	0,61443363	0,125129038	0,071007	0,01446
Ecotoxicity, freshwater - inorganics	0,60281563	0,12276304	0,044883	0,00914
Ecotoxicity, freshwater - organics	0,011617994	0,002365997	0,026124	0,00532
Particulate matter	2,78002E-09	5,66148E-10	4,42E-10	9E-11
Eutrophication, marine	7,81952E-05	1,59244E-05	1,39E-05	2,82E-06
Eutrophication, freshwater	1,92289E-05	3,91596E-06	9,77E-06	1,99E-06
Eutrophication, terrestrial	0,000575153	0,00011713	0,000131	2,68E-05
Human toxicity, cancer	1,61318E-11	3,28523E-12	4,18E-12	8,52E-13
Human toxicity, cancer - inorganics	5,57896E-12	1,13615E-12	2,26E-12	4,61E-13
Human toxicity, cancer - organics	1,05528E-11	2,14908E-12	1,92E-12	3,9E-13
Human toxicity, non-cancer	5,42401E-10	1,1046E-10	1,99E-10	4,05E-11
Human toxicity, non-cancer - inorganics	5,14241E-10	1,04725E-10	1,87E-10	3,81E-11
Human toxicity, non-cancer - organics	2,816E-11	5,73476E-12	1,22E-11	2,48E-12
Ionising radiation	0,010753364	0,002189916	0,005672	0,001155
Land use	0,11702563	0,023832199	0,06126	0,012476

Ozone depletion	1,22655E-07	2,49786E-08	5,75E-10	1,17E-10
Photochemical ozone formation	0,000158061	3,21891E-05	6,79E-05	1,38E-05
Resource use, fossils	0,88362382	0,179949458	0,43421	0,088427
Resource use, minerals and metals	3,19237E-07	6,50124E-08	1,82E-07	3,71E-08
Water use	0,011637952	0,002370062	0,004136	0,000842

Table 36. WP3 cradle-to-gate+EoL impact assessment results – Membrane

Impact category	**Generic membrane**		**CENmat membrane**	
	Reference flow: 1 REDHy system	Reference flow: Functional unit (1 kg H_2)	Reference flow: 1 REDHy system	Reference flow: Functional unit (1 kg H_2)
Acidification	0,005771384	0,001175	0,005269742	0,001073
Climate change	0,964568	0,196434	0,9640056	0,196319
Climate change - Biogenic	0,001941103	0,000395	0,001848566	0,000376
Climate change - Fossil	0,95989935	0,195483	0,95957545	0,195417
Climate change - Land use and LU change	0,002727534	0,000555	0,002581586	0,000526
Ecotoxicity, freshwater	23,272279	4,739386	4,70747545	0,958675
Ecotoxicity, freshwater - inorganics	23,1828295	4,721169	3,1962537	0,650915
Ecotoxicity, freshwater - organics	0,08944978	0,018216	1,5112218	0,307759
Particulate matter	2,30699E-08	4,7E-09	2,06798E-08	4,21E-09
Eutrophication, marine	0,000885056	0,00018	0,000865728	0,000176
Eutrophication, freshwater	0,000902746	0,000184	0,000863292	0,000176
Eutrophication, terrestrial	0,007844273	0,001597	0,007735933	0,001575
Human toxicity, cancer	2,73052E-10	5,56E-11	3,22855E-10	6,57E-11
Human toxicity, cancer - inorganics	1,59446E-10	3,25E-11	1,53737E-10	3,13E-11
Human toxicity, cancer - organics	1,13606E-10	2,31E-11	1,69118E-10	3,44E-11
Human toxicity, non-cancer	1,47311E-08	3E-09	1,4174E-08	2,89E-09
Human toxicity, non-cancer - inorganics	1,4009E-08	2,85E-09	1,34273E-08	2,73E-09

Human toxicity, non-cancer - organics	7,22056E-10	1,47E-10	7,46779E-10	1,52E-10
Ionising radiation	0,59391815	0,120951	0,55810025	0,113657
Land use	4,28689955	0,873025	4,13127885	0,841332
Ozone depletion	1,90687E-08	3,88E-09	2,1077E-08	4,29E-09
Photochemical ozone formation	0,002579085	0,000525	0,002887868	0,000588
Resource use, fossils	21,967563	4,473681	22,268903	4,535049
Resource use, minerals and metals	1,27032E-05	2,59E-06	1,22071E-05	2,49E-06
Water use	0,266562375	0,054285	0,25678827	0,052295

Table 37. WP4 cradle-to-gate+EoL impact assessment results – Electrodes

Impact category	**GO electrode**	
	Ref. Flow: 1 REDHy system	**Ref. Flow: functional unit (1 kg H_2)**
Acidification	3,7944219	0,772731733
Climate change	655,77257	133,5476886
Climate change - Biogenic	1,3603385	0,277032116
Climate change - Fossil	652,49923	132,8810749
Climate change - Land use and LU change	1,9130026	0,389581826
Ecotoxicity, freshwater	2191,0014	446,1961144
Ecotoxicity, freshwater - inorganics	2168,4199	441,5974055
Ecotoxicity, freshwater - organics	22,581521	4,598713139
Particulate matter	1,37115E-05	2,79233E-06
Eutrophication, marine	0,5990937	0,122005071
Eutrophication, freshwater	0,62300004	0,126873583
Eutrophication, terrestrial	5,3034083	1,080035903
Human toxicity, cancer	2,02297E-07	4,11977E-08
Human toxicity, cancer - inorganics	1,09913E-07	2,23838E-08
Human toxicity, cancer - organics	9,23839E-08	1,88139E-08
Human toxicity, non-cancer	1,01228E-05	2,06151E-06
Human toxicity, non-cancer - inorganics	9,65532E-06	1,9663E-06
Human toxicity, non-cancer - organics	4,67511E-07	9,52082E-08
Ionising radiation	418,24702	85,1757535
Land use	2940,1381	598,7573517
Ozone depletion	1,31846E-05	2,68504E-06
Photochemical ozone formation	1,7005712	0,3463203
Resource use, fossils	15001,642	3055,07535
Resource use, minerals and metals	0,008753032	0,00178255
Water use	174,08081	35,45145202

Table 38. WP5 cradle-to-gate+EoL impact assessment results – Catalysts

Impact category	MoS2	MoS2/C	NiFe	NiMo
Reference flow: 1 REDHy system				
Acidification	0,014276	0,014277	0,022358	0,029152
Climate change	2,13904	2,1393	4,380495	5,522231
Climate change - Biogenic	0,003947	0,003947	0,005863	0,008517
Climate change - Fossil	2,129551	2,12981	4,366828	5,502129
Climate change - Land use and LU change	0,005543	0,005543	0,007805	0,011585
Ecotoxicity, freshwater	6,700625	6,701004	20,85572	24,11557
Ecotoxicity, freshwater - inorganics	6,63641	6,63676	20,64953	23,88342
Ecotoxicity, freshwater - organics	0,064215	0,064244	0,206186	0,232144
Particulate matter	6,67E-08	6,67E-08	1,25E-07	1,46E-07
Eutrophication, marine	0,001842	0,001842	0,009537	0,010097
Eutrophication, freshwater	0,001856	0,001856	0,002548	0,003785
Eutrophication, terrestrial	0,016521	0,016523	0,045839	0,054109
Human toxicity, cancer	8,33E-10	8,33E-10	1,04E-09	1,38E-09
Human toxicity, cancer - inorganics	3,26E-10	3,26E-10	5,57E-10	7,65E-10
Human toxicity, cancer - organics	5,06E-10	5,06E-10	4,84E-10	6,1E-10
Human toxicity, non-cancer	2,97E-08	2,97E-08	5,25E-08	7,16E-08
Human toxicity, non-cancer - inorganics	2,83E-08	2,83E-08	4,7E-08	6,54E-08
Human toxicity, non-cancer - organics	1,45E-09	1,45E-09	5,52E-09	6,23E-09
Ionising radiation	1,209077	1,209079	1,507499	2,352665
Land use	8,881628	8,882194	14,37423	19,9837
Ozone depletion	4,09E-08	4,09E-08	5,83E-08	8,16E-08
Photochemical ozone formation	0,007101	0,007103	0,010205	0,013248
Resource use, fossils	46,92292	46,93143	69,02782	97,90785
Resource use, minerals and metals	2,65E-05	2,65E-05	4,82E-05	6,62E-05
Water use	0,601018	0,601034	1,200402	1,46354

Impact category	MoS2	MoS2/C	NiFe	NiMo
Reference flow: functional unit (1 kg H_2)				
Acidification	0,002907	0,002908	0,004553	0,005937
Climate change	0,435614	0,435667	0,892085	1,124599
Climate change - Biogenic	0,000804	0,000804	0,001194	0,001734
Climate change - Fossil	0,433682	0,433735	0,889302	1,120505
Climate change - Land use and LU change	0,001129	0,001129	0,001589	0,002359
Ecotoxicity, freshwater	1,364578	1,364655	4,247255	4,911121
Ecotoxicity, freshwater - inorganics	1,351501	1,351572	4,205265	4,863845
Ecotoxicity, freshwater - organics	0,013077	0,013083	0,04199	0,047276
Particulate matter	1,36E-08	1,36E-08	2,55E-08	2,96E-08
Eutrophication, marine	0,000375	0,000375	0,001942	0,002056
Eutrophication, freshwater	0,000378	0,000378	0,000519	0,000771
Eutrophication, terrestrial	0,003365	0,003365	0,009335	0,011019
Human toxicity, cancer	1,7E-10	1,7E-10	2,12E-10	2,8E-10

Human toxicity, cancer - inorganics	6,64E-11	6,64E-11	1,13E-10	1,56E-10
Human toxicity, cancer - organics	1,03E-10	1,03E-10	9,86E-11	1,24E-10
Human toxicity, non-cancer	6,06E-09	6,06E-09	1,07E-08	1,46E-08
Human toxicity, non-cancer - inorganics	5,76E-09	5,76E-09	9,56E-09	1,33E-08
Human toxicity, non-cancer - organics	2,95E-10	2,95E-10	1,12E-09	1,27E-09
Ionising radiation	0,246228	0,246228	0,307001	0,479119
Land use	1,808738	1,808853	2,927303	4,069668
Ozone depletion	8,33E-09	8,33E-09	1,19E-08	1,66E-08
Photochemical ozone formation	0,001446	0,001446	0,002078	0,002698
Resource use, fossils	9,555825	9,557557	14,05747	19,93887
Resource use, minerals and metals	5,4E-06	5,4E-06	9,82E-06	1,35E-05
Water use	0,122397	0,1224	0,244461	0,298049

Table 39. WP6 cradle-to-gate+EoL impact assessment results – Stack and BoP

Impact Category	BP graphite/PP	BP Ni	BP Stainless Steel	BP anode SS cathode graphite/PP
Reference flow: 1 REDHy system				
Acidification	2,984247	15,906586	3,2328499	3,1085378
Climate change	464,62717	612,48053	509,44857	487,03507
Climate change - Biogenic	4,5329432	5,1660288	5,070601	4,8017715
Climate change - Fossil	459,57051	606,34639	503,80272	481,68382
Climate change - Land use and LU change	0,5237118	0,96810685	0,57524665	0,54947817
Ecotoxicity, freshwater	5765,8264	8756,9061	6323,1938	6044,5029
Ecotoxicity, freshwater - inorganics	5719,6736	8696,6393	6273,2882	5996,4739
Ecotoxicity, freshwater - organics	46,152731	60,266811	49,905598	48,028994
Particulate matter	3,64193E-05	5,97605E-05	4,02594E-05	3,83392E-05
Eutrophication, marine	0,50130754	0,76834772	0,5500334	0,52566664
Eutrophication, freshwater	0,40011342	0,52933565	0,44113226	0,42062261
Eutrophication, terrestrial	5,2539367	7,9985482	5,7568803	5,5053668
Human toxicity, cancer	5,30138E-07	8,47094E-07	5,82692E-07	5,56415E-07
Human toxicity, cancer - inorganics	3,99781E-07	6,9635E-07	4,41408E-07	4,20594E-07
Human toxicity, cancer - organics	1,30357E-07	1,50744E-07	1,41283E-07	1,3582E-07
Human toxicity, non-cancer	1,40595E-05	1,81865E-05	1,49237E-05	1,44916E-05
Human toxicity, non-cancer - inorganics	1,34628E-05	1,74008E-05	1,43093E-05	1,3886E-05

Human toxicity, non-cancer - organics	5,96698E-07	7,8565E-07	6,14398E-07	6,05546E-07
Ionising radiation	34,250583	68,264124	37,708463	35,979452
Land use	2589,4269	3708,9975	2853,8463	2721,6203
Ozone depletion	5,0738E-06	6,95763E-06	5,2355E-06	5,15459E-06
Photochemical ozone formation	1,7398367	3,4756442	1,8913182	1,8155621
Resource use, fossils	5965,1866	8186,9257	6434,9531	6200,0304
Resource use, minerals and metals	0,017118681	0,034726768	0,018208116	0,017663385
Water use	122,1869	700,2856	133,87365	128,03012

Impact category	**BP graphite/ PP**	**BP Ni**	**BP Stainless Steel**	**BP anode SS cathode graphite/PP**
Reference flow: Functional Unit (1 kg H_2)				
Acidification	0,60774	3,239367	0,658368	0,633052
Climate change	94,62104	124,7313	103,7489	99,1844
Climate change - Biogenic	0,923131	1,052059	1,032625	0,977878
Climate change - Fossil	93,59126	123,4821	102,5991	98,09462
Climate change - Land use and LU change	0,106654	0,197154	0,117149	0,111901
Ecotoxicity, freshwater	1174,207	1783,339	1287,715	1230,959
Ecotoxicity, freshwater - inorganics	1164,808	1771,065	1277,551	1221,178
Ecotoxicity, freshwater - organics	9,398976	12,2733	10,16324	9,781076
Particulate matter	7,42E-06	1,22E-05	8,2E-06	7,81E-06
Eutrophication, marine	0,102091	0,156474	0,112014	0,107052
Eutrophication, freshwater	0,081483	0,107799	0,089836	0,08566
Eutrophication, terrestrial	1,069961	1,6289	1,172385	1,121165
Human toxicity, cancer	1,08E-07	1,73E-07	1,19E-07	1,13E-07
Human toxicity, cancer - inorganics	8,14E-08	1,42E-07	8,99E-08	8,57E-08
Human toxicity, cancer - organics	2,65E-08	3,07E-08	2,88E-08	2,77E-08

Human toxicity, non-cancer	2,86E-06	3,7E-06	3,04E-06	2,95E-06
Human toxicity, non-cancer - inorganics	2,74E-06	3,54E-06	2,91E-06	2,83E-06
Human toxicity, non-cancer - organics	1,22E-07	1,6E-07	1,25E-07	1,23E-07
Ionising radiation	6,975111	13,90195	7,679306	7,327194
Land use	527,3352	755,3351	581,1841	554,2563
Ozone depletion	1,03E-06	1,42E-06	1,07E-06	1,05E-06
Photochemical ozone formation	0,354317	0,707813	0,385166	0,369738
Resource use, fossils	1214,807	1667,262	1310,474	1262,632
Resource use, minerals and metals	0,003486	0,007072	0,003708	0,003597
Water use	24,88329	142,6127	27,26329	26,07326

Table 40. Transport to end user impacts (referred to functional unit, 1 kg H_2)

Impact category	Transport to end user
Acidification	0,020679439
Climate change	5,408485862
Climate change - Biogenic	0,001138901
Climate change - Fossil	5,405314116
Climate change - Land use and LU change	0,002032839
Ecotoxicity, freshwater	13,80024714
Ecotoxicity, freshwater - inorganics	13,46984159
Ecotoxicity, freshwater - organics	0,330405473
Particulate matter	3,27489E-07
Eutrophication, marine	0,007412455
Eutrophication, freshwater	0,00044577
Eutrophication, terrestrial	0,080759627
Human toxicity, cancer	9,97453E-10
Human toxicity, cancer - inorganics	4,53919E-10
Human toxicity, cancer - organics	5,43534E-10
Human toxicity, non-cancer	4,58849E-08
Human toxicity, non-cancer - inorganics	4,28358E-08
Human toxicity, non-cancer - organics	3,04911E-09
Ionising radiation	0,138917334
Land use	31,4789665
Ozone depletion	1,17964E-07
Photochemical ozone formation	0,029802726

Resource use, fossils	76,33465625
Resource use, minerals and metals	2,52311E-05
Water use	0,30377439

Table 41.Use phase impact assessment (referred to functional unit, 1 kg H_2)

Impact category	Stack, electricity SOLAR and WIND average	Wastewater, MoS2	Wastewater, MoS2/C	Wastewater, NiFe	Wastewater, NiMo	KOH	Ultrapure water, as feedstock
Acidification	2,2E-02	2,7E-07	2,7E-07	3,8E-07	3,8E-07	1,4E-04	1,0E-04
Climate change	3,4E+00	5,4E-05	5,4E-05	7,7E-05	7,7E-05	2,6E-02	2,2E-02
Climate change - Biogenic	9,1E-03	7,5E-06	7,5E-06	1,1E-05	1,1E-05	4,1E-05	4,3E-05
Climate change - Fossil	3,4E+00	4,7E-05	4,7E-05	6,7E-05	6,7E-05	2,6E-02	2,2E-02
Climate change - Land use and LU change	6,1E-03	5,5E-08	5,5E-08	7,9E-08	7,9E-08	4,2E-05	5,6E-05
Ecotoxicity, freshwater	2,6E+01	1,2E-02	1,2E-02	1,8E-02	1,8E-02	5,8E-01	1,7E-01
Ecotoxicity, freshwater - inorganics	2,6E+01	1,2E-02	1,2E-02	1,8E-02	1,8E-02	5,8E-01	1,7E-01
Ecotoxicity, freshwater - organics	4,5E-01	3,5E-06	3,5E-06	5,0E-06	5,0E-06	2,1E-03	8,0E-04
Particulate matter	2,7E-07	3,1E-12	3,1E-12	4,4E-12	4,4E-12	1,6E-09	5,8E-10
Eutrophication, marine	3,8E-03	2,3E-06	2,3E-06	3,2E-06	3,2E-06	2,9E-05	2,1E-04
Eutrophication, freshwater	1,8E-03	2,5E-07	2,5E-07	3,5E-07	3,5E-07	1,1E-05	4,2E-04
Eutrophication, terrestrial	4,0E-02	8,3E-07	8,3E-07	1,2E-06	1,2E-06	2,9E-04	1,7E-04
Human toxicity, cancer	2,4E-09	5,9E-14	5,9E-14	8,4E-14	8,4E-14	1,0E-10	8,1E-12
Human toxicity, cancer - inorganics	1,1E-09	4,6E-14	4,6E-14	6,6E-14	6,6E-14	3,3E-12	4,7E-12
Human toxicity, cancer - organics	1,3E-09	1,3E-14	1,3E-14	1,9E-14	1,9E-14	9,8E-11	3,3E-12

Human toxicity, non-cancer	1,1E-07	8,5E-12	8,5E-12	1,2E-11	1,2E-11	2,8E-10	3,7E-10
Human toxicity, non-cancer - inorganics	1,0E-07	8,5E-12	8,5E-12	1,2E-11	1,2E-11	2,7E-10	3,6E-10
Human toxicity, non-cancer - organics	3,9E-09	3,8E-14	3,8E-14	5,4E-14	5,4E-14	1,5E-11	5,4E-12
Ionising radiation	2,4E-01	9,4E-06	9,4E-06	1,3E-05	1,3E-05	2,5E-03	1,2E-02
Land use	4,4E+02	2,7E-04	2,7E-04	3,8E-04	3,8E-04	1,1E-01	7,5E-02
Ozone depletion	2,7E-07	6,7E-13	6,7E-13	9,6E-13	9,6E-13	3,1E-10	2,0E-08
Photochemical ozone formation	1,4E-02	1,8E-07	1,8E-07	2,6E-07	2,6E-07	9,0E-05	5,4E-05
Resource use, fossils	4,2E+01	6,3E-04	6,3E-04	9,0E-04	9,0E-04	3,3E-01	4,6E-01
Resource use, minerals and metals	1,4E-04	2,7E-10	2,7E-10	3,9E-10	3,9E-10	2,6E-07	6,5E-08
Water use	2,9E+00	-6,1E-03	-6,1E-03	-8,7E-03	-8,7E-03	6,9E-03	5,8E-01

Table 42. Cradle-to-grave impact assessment results – for the 4 analyzed BPPs options

Impact category	MoS2/C + NiFe BP graphite/PP + CENMAT membrane	MoS2/C +NiFe +BP Ni + CENMAT membrane	MoS2/C + NiFe + BP SS + CENMAT membrane	MoS2/C + NiFe + BP anode/cathode differ + CENMAT membrane
Reference flow: 1 kg H2				
Acidification	1,4E+00	4,1E+00	1,2E+00	1,5E+00
Climate change	2,4E+02	2,7E+02	2,4E+02	2,4E+02
Climate change - Biogenic	1,2E+00	1,3E+00	5,1E-01	1,3E+00
Climate change - Fossil	2,4E+02	2,7E+02	1,6E+03	2,4E+02
Climate change - Land use and LU change	5,1E-01	6,0E-01	1,6E+03	5,1E-01
Ecotoxicity, freshwater	1,7E+03	2,3E+03	5,5E+01	1,7E+03
Ecotoxicity, freshwater - inorganics	1,7E+03	2,3E+03	4,0E+01	1,7E+03
Ecotoxicity, freshwater - organics	1,5E+01	1,8E+01	1,0E+00	1,6E+01
Particulate matter	1,1E-05	1,6E-05	2,1E-01	1,1E-05
Eutrophication, marine	2,4E-01	2,9E-01	2,2E+00	2,4E-01
Eutrophication, freshwater	2,1E-01	2,4E-01	2,7E-03	2,2E-01
Eutrophication, terrestrial	2,3E+00	2,8E+00	1,2E-01	2,3E+00

Human toxicity, cancer	1,5E-07	2,2E-07	4,9E-08	1,6E-07
Human toxicity, cancer - inorganics	1,1E-07	1,7E-07	4,9E-06	1,1E-07
Human toxicity, cancer - organics	4,8E-08	5,2E-08	4,7E-06	4,9E-08
Human toxicity, non-cancer	5,1E-06	5,9E-06	3,7E-07	5,2E-06
Human toxicity, non-cancer - inorganics	4,9E-06	5,7E-06	9,3E+01	5,0E-06
Human toxicity, non-cancer - organics	2,3E-07	2,6E-07	1,1E+03	2,3E-07
Ionising radiation	9,3E+01	1,0E+02	3,9E-01	9,4E+01
Land use	1,6E+03	1,8E+03	4,7E+02	1,6E+03
Ozone depletion	4,2E-06	4,6E-06	4,3E+03	4,2E-06
Photochemical ozone formation	7,5E-01	1,1E+00	4,9E-02	7,6E-01
Resource use, fossils	4,4E+03	4,9E+03	1,8E+02	4,5E+03
Resource use, minerals and metals	5,4E-03	9,0E-03	1,6E-04	5,6E-03
Water use	6,5E+01	1,8E+02	3,8E+00	6,6E+01