HYGRID

FLEXIBLE HYBRID SEPARATION SYSTEM FOR H2 RECOVERY FROM NG GRIDS

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WP9 – Environmental LCA and economic assessment

D.9.2
Preliminary environmental LCA

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Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
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CON	Confidential, only for members of the Consortium	

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ACRONYMS and ABBREVIATIONS

CO_2	carbon dioxide
CSM	Carbon Sieve Membranes
DALY	disability adjusted life-years
EHP	Electrochemical Hydrogen Purifier
EPFL	Ecole Polytéchnique Fédérale Lausanne (Swiss Federal Institute of Technology in Lausanne)
FU	functional unit
g	gram
GHG	greenhouse gas
H_2	Hydrogen
H_2O	water
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	kilogram
kg CO_2-eq	kilogram of carbon dioxide equivalent
kWh	kilowatt hour
LCA	life cycle assessment
LCC	life cycle costing
LCI	life cycle inventory
LCIA	life cycle impact assessment
m^3	cubic metre
mg	milligram
MJ	megajoule
n/a	not applicable
NOx	nitrogen oxides
O_2	oxygen (gas)
PDF.m^2.y	potentially disappeared fraction per square metre of land per year

PM	particulate matter
PSA	Pressure Swing Adsorption
SOx	sulphur oxides
TBD	to be decided
TSA	Temperature Swing Adsorption
WP	work package
µm	micrometre

1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

The key objective of the H2020 EU research project HyGrid is the design, scale-up and validation of a novel membrane-based hybrid technology for the direct separation of hydrogen from natural gas grids. The focus of the project will be on the hydrogen separation through a combination of membranes, electrochemical separation (EHP) and temperature swing adsorption (TSA) to be able to decrease the total cost of hydrogen recovery. The project targets a pure hydrogen separation system with low power and at low cost. A pilot designed for 25 kg/day of hydrogen will be built and tested. Emissions should be reduced respectively not be higher than conventional technologies.

In order to determine the environmental impacts associated with hydrogen production via the HyGrid technology compared to the reference technology, pressure swing adsorption (PSA), Quantis is tasked with performing an environmental life cycle assessment (LCA). LCA is an internationally recognized approach that has been standardized by the International Organization for Standardization (ISO) (ISO 14040:2006, ISO 14044:2006) to evaluate and assess the potential environmental and human health impacts associated with products and services throughout their life cycles. LCA is used to identify hotspots and thus opportunities to improve the environmental performance of products/processes at various stages along their life cycles.

This deliverable details the preliminary results obtained for the screening LCA based on data obtained up to M24 of the HyGrid project. It aims at identifying the main areas of environmental impacts to guide the design and development of the novel hydrogen separation technology towards more sustainable solutions.

The screening environmental LCA, which is conducted on a lower level of detail than a full LCA, will help to identify the most probable hotspots in the life cycle and where more in-depth information is necessary. Additionally, it aims to provide recommendations on the most promising options and configurations from an environmental point of view.

This study assesses the life cycle of each technology, PSA and HyGrid, from the extraction and processing of raw materials through the production of hydrogen (cradle-to-gate approach). A cradle-to-grave approach will be followed for the final LCA.

The functional unit for this study is:

The recovery from an average European natural gas grid of 1 kg of hydrogen with a purity of at least 99.97%.

Primary data have been collected from partners involved in WPs 3, 4, 5, 7 and 8 to date. Each plant design is based on a hydrogen production rate of 25 kg H_2/day. All life cycle inventory data are taken from the ecoinvent database v3.3.

The peer-reviewed impact assessment method IMPACT 2002+ (vQ2.28) is used for the impact assessment phase of the study, evaluating the impact on the following environmental impact categories:

- Greenhouse gas (GHG) emissions (carbon footprint)
- Water withdrawal (water footprint)
- Ecosystem quality
- Resource depletion
- Human health

The results based on the preliminary assessment show that the HyGrid technology is less impacting in the use stage than the PSA for all indicators. The main reason for this trend is the, in comparison, lower demand for energy for the use phase.

The new configuration (No. 16) is the same in terms of components setup as the original setup, but operates as a smaller feed flow. It is therefore slightly less efficient than the original prototype in terms of use of material per output and thus needs more electricity per kg H_2 produced, which increases the impact respectively.

The preliminary results showed that the electricity usage and the material demand in metals are significant parameters that affect the impacts of most indicators.

A more detailed final environmental LCA will follow and build upon the screening environmental LCA, aiming at providing a complete LCA of the investigated HyGrid technology.

1.2 Brief description of the state of the art and the innovation

Since the systems under study are currently being developed within the HyGrid project, no LCA results or literature on this specific topic exist. The results of the LCA of the hydrogen recovery systems developed within HyGrid will therefore shed new light on the contributions which these devices can bring in the shift towards more sustainable energy distribution systems.

1.3 Deviation from objectives

No deviation from the objectives.

2 INTRODUCTION

This deliverable, D9.2, presents the life cycle assessment (LCA) methodology and the scope of the study, the data and the assumptions used, and finally the screening LCA results of the HyGrid technology with a comparison to a reference technology.

2.1 Context and background

Heightened concern around the environmental and social sustainability of society's consumption habits has focused attention on understanding and proactively managing the potential environmental and societal consequences of production and consumption of products and services. Nearly all major product producers now consider environmental and social impacts as a key decision point in material selection, and sustainability is a recognized point of competition in many industries.

A leading tool for assessing environmental performance is LCA, a method defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 2006a; ISO 2006b). LCA is an internationally-recognized approach that evaluates the relative potential environmental and human health impacts of products and services throughout their life cycle, beginning with raw material extraction and including all aspects of transportation, manufacturing, use, and end-of-life treatment.

It is important to note that LCA does not exactly quantify the real impacts of a product or service due to data availability and modelling challenges. However, it allows for estimating and understanding the potential environmental impacts that a system might cause over its typical life cycle, by quantifying (within the current scientific limitations) the likely emissions produced and resources consumed. Hence, environmental impacts calculated through LCA should not be interpreted as absolute, but rather as relative values within the framework of the study. Ultimately, this is not a limitation of the methodology, since LCA is generally used to compare different systems performing the same function, where it is the relative differences in environmental impacts which are key for identifying the solution which performs best.

Among other uses, LCA can identify opportunities to improve the environmental performance of products, inform decision-making, and support marketing, communication, and educational efforts. The importance of the life cycle view in sustainability decision-making is sufficiently strong that over the past several decades it has become the principal approach to evaluate a broad range of environmental problems, to identify social risks and to help make decisions within the complex arena of socio-environmental sustainability.

The aim of the HyGrid project is to develop innovative hydrogen recovery systems based on the combined use of membranes, electrochemical hydrogen purification (EHP) and temperature swing adsorption (TSA). The idea is to use such systems to recover hydrogen from the mixture of gases flowing through the natural gas grid. This would allow for using the existing natural gas grid as a transport and storage system for hydrogen avoiding having to build a dedicated hydrogen distribution grid and hence avoiding the related costs.

The aim of WP9 is to perform an environmental LCA and economic assessment of the hydrogen recovery systems developed within HyGrid. Further, since the LCA will accompany the research, the idea is to use the LCA work to steer the development of the systems towards more sustainable solutions. Finally, a comparison will be made between the life cycle performance of the systems developed within HyGrid and the conventional technology currently able to deliver the same service.

This deliverable presents the results of the first step of the LCA analysis (screening LCA), which allows for the calculation of a global environmental assessment of the new technology and the identification of the hotspots for each process and each environmental indicator, based on the data provided by other WPs. For the second step of the LCA analysis (detailed LCA, D9.3 due M36), the calculations will be revised and extended with updated data and assumptions. Emphasis will be set on the process units generating the largest impacts ("hotspots") identified in the present screening analysis.

The results of this project are intended for internal use by HyGrid partners. The study at this stage does not comply with all the ISO 14040 requirements to make competitive public statements or marketing claims. While it is not intended to support such purposes, it provides a foundation for additional work aiming at meeting such purposes. Communication of the results presented in this report outside HyGrid should be conducted with caution and accompanied by a statement that the findings are based on an LCA that doesn't support public claims.

2.2 Life cycle assessment approach

An LCA is comprised of four phases as shown in Figure 1 below:

1. **Goal and scope definition:** defining the purposes of the study, determining the boundaries of the system life cycle in question and identifying important assumptions that will be made;
2. **Inventory analysis:** compiling a complete record of the important material and energy flows throughout the life-cycle, in additional to releases of pollutants and other environmental aspects being studied;
3. **Impact assessment**: using the inventory compiled in the prior stage to create a clear and concise picture of environmental impacts among a limited set of understandable impact categories; and
4. **Interpretation**: identifying the meaning of the results of the inventory and impact assessment relative to the goals of the study.

LCA is best practiced as an iterative process, where the findings at each stage influence changes and improvements in the others to arrive at a study design that is of adequate quality to meet the defined goals. The principles, framework, requirements and guidelines to perform an LCA are described by the international standards ISO 14040 series (ISO 2006).

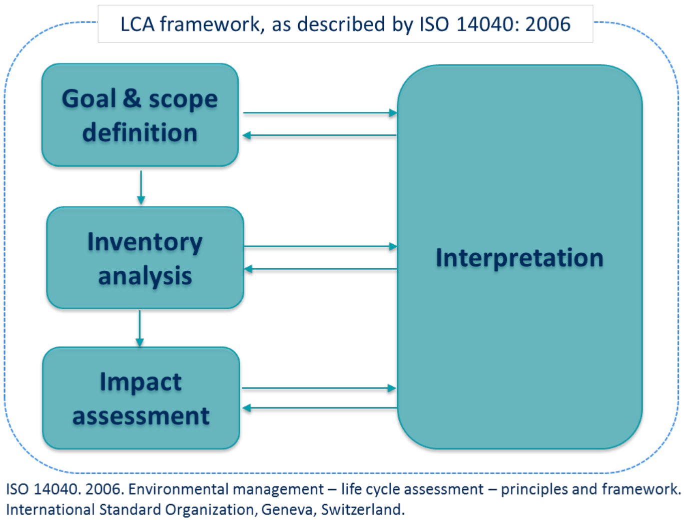

Figure 1: LCA framework (ISO 2006)

3 GOAL AND SCOPE DEFINITION

The goal and scope of the study, along with the methodological framework of the LCA, has been described in D9.1. We copy here the content of D9.1 to facilitate the comprehension of the study and amend/complete where necessary to account for decisions made at the M24 meeting.

3.1 Objectives

The aim of WP9 is to perform an environmental LCA and economic assessment of the hydrogen recovery systems developed within HyGrid. This will allow understanding what environmental impacts could be caused by the investigated systems and what economic burden will result from their production, use and end-of-life. In order to further asses the advantages and challenges connected to the development of HyGrid's hydrogen recovery systems, the results of the environmental and economic life cycle analysis will be compared against those of the currently available technology typically used for the recovery of hydrogen from a gas mixture mainly comprising natural gas. Finally, by doing an accompanying study which develops together with the findings of the other WPs, the idea is to steer the project towards the realisation of more environmentally friendly hydrogen recovery systems by highlighting along the way critical environmental issues which may be optimised.

3.2 Intended audience

The results of this screening LCA are not intended for public disclosure but only destined to the members of the consortium (including the Commission Services).

3.3 Description of the reference systems

The hydrogen recovery system developed within HyGrid comprises three successive recovery steps. As schematically shown in **Figure 2**, the natural gas mixture is first sent through a membrane system, then through electrochemical hydrogen purification

(EHP). The separated hydrogen is then sent to the temperature swing adsorption (TSA) unit.

Figure 2: Hydrogen recovery system within HyGrid.

Various membrane systems are currently being investigated. Particularly, Palladium-based and Carbon Sieve Membranes (CSMs) will be considered. Moreover, the impact on the system's performance of metallic and ceramic supports for the membranes will also be analysed. The life cycle analysis will, as far as data availability will allow, address the various subsystems (membranes, EHP and TSA) as well as the different membrane types and supports in order to try and identify the most sustainable solutions. **Table 1** summarises the key target parameters for the recovery systems addressed within HyGrid (DoW, 2015).

Table 1: Target parameters for HyGrid's hydrogen recovery systems

	P [bar]	T [°C]	H_2 production [kg/day]	H_2 cost [€/kg_{H2}]	Power consumption [kWh/kg_{H2}]	Payback time [years]	Lifetime [years]
HyGrid System	0.03-80	T<400	>25	<1.5	<5	<6	>15

In terms of reference technology, initially, it was identified that the most relevant technology which could deliver a hydrogen recovery service similar to the one provided by HyGrid's systems is 5-bed pressure swing adsorption (PSA) (see also deliverable D9.1). It was therefore decided that 5-bed PSA will be used as reference technology against which the environmental and cost performance of the recovery systems developed within HyGrid will be compared. Calculations from the partners showed however that PSA is not able to separate the HyGrid gases at the concentrations required and that there is no existing membrane system which can be considered as alternative to the HyGrid system. In the next phase, possible reference systems will be explored and discussed.

3.4 Function and functional unit

The functional unit quantifies the performance of a product system and is used as a reference unit for which the life cycle assessment study is performed and the results are presented. It is therefore critical that this parameter is clearly defined and measurable.

The purpose (or function) of the systems developed within HyGrid is the recovery of pure hydrogen from a mixture of gases mainly comprising natural gas and available from the natural gas grid. Moreover, since one potential application of these recovery systems is to use the hydrogen in automotive systems, the recovered hydrogen should be of sufficient purity to be used in fuel cell systems for road vehicles.

The functional unit for the analysis will therefore be:

The recovery from an average European natural gas grid of 1 kg of hydrogen with a purity of at least 99.97%

The reference flow is therefore 1 kg of hydrogen with a purity of at least 99.97%.

3.5 System boundaries

The system boundaries define what processes will be considered in the analysis. The aim of the environmental and economic assessment in HyGrid is to identify the relevant mechanisms in the life cycle of the hydrogen recovery systems which might impact the environment and to understand its key cost aspects. As such, as far as data availability will allow, the target is to try and include all potential main impact and cost contributors. As schematically shown in **Figure 3** for the environmental assessment, this means that all emissions caused and resources consumed by processes such as the production of the raw materials and energy vectors required for the manufacturing, use and end-of-life will be included in the analysis. This includes the impacts deriving from the extraction of the raw materials, production or dismantling infrastructure, all transport services which might be required as well as waste disposal systems or the generation of the needed electricity or fuels. For the cost analysis, the same approach will be used, only focusing on the cost information for each item considered.

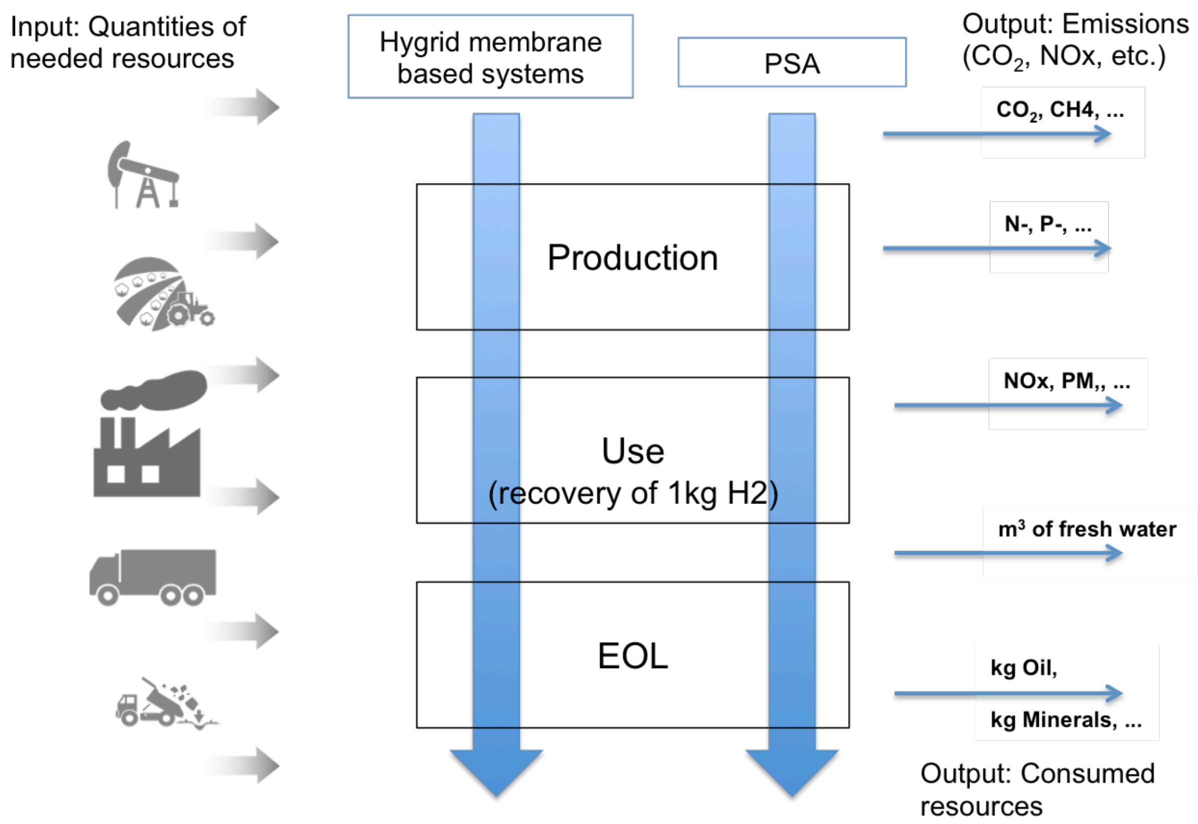

Figure 3: System boundaries in the LCA of the hydrogen recovery systems.

Following the definition of the functional unit, the results will be scaled to the life cycle environmental and cost impacts for the recovery of 1 kg of hydrogen. As already mentioned above, for the recovery systems developed within HyGrid, the analysis will address the various sub-systems (membranes, EHP and TSA) as well as the various membrane types and supports. This will highlight the hot spots of the systems (meaning the sub-processes responsible for the largest environmental impacts and cost contributions) and thereby help to identify the potential for optimisation.

While the key analysis will address the life cycle related to the recovery of 1 kg of hydrogen, in a second step, the focus will also be shifted to the use of the recovered hydrogen in a fuel cell automotive application including the life cycle impacts coming from, amongst other things, the fuel cell vehicle and road infrastructure and the specific hydrogen consumption used per km for current fuel cell vehicles (**Figure 4**). Including this specific application of the recovered hydrogen in the analysis will help to understand the relative contribution of the recovery of the hydrogen as opposed to the other processes involved in its use (e.g. the life cycle of the vehicle and road infrastructure as opposed to the production of the hydrogen distributed through the natural gas grid). Since about 95% of the hydrogen produced today is obtained from steam reforming of natural gas[1], this hydrogen production chain will be considered in this part of the analysis.

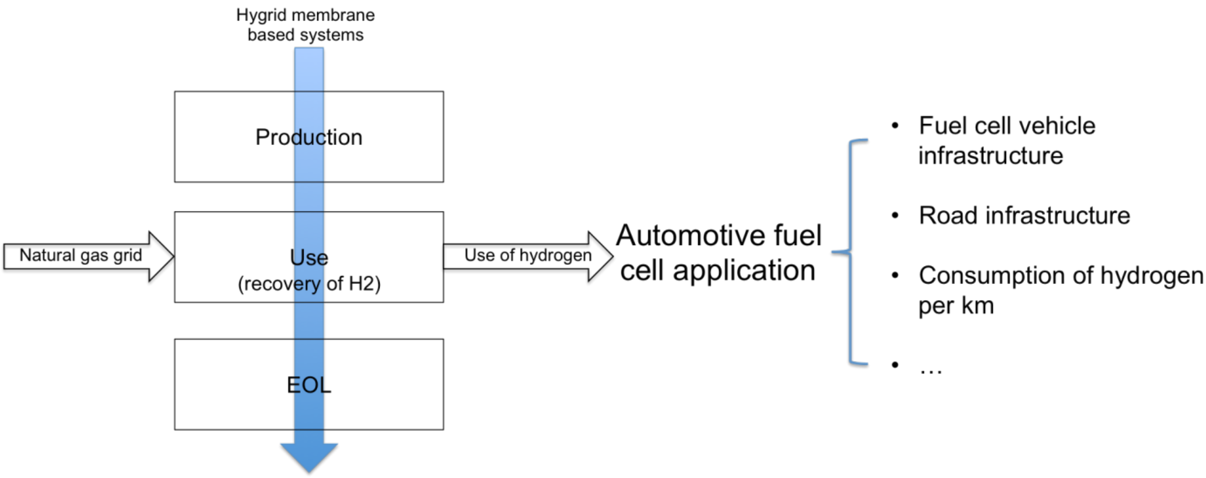

Figure 4: Impact analysis for HyGrid's hydrogen recovery systems including the use of the hydrogen in a fuel cell vehicle.

3.6 Allocation methodology

According to ISO, the term allocation refers to the partitioning of the input/or output flows of a process to the product system under study. As there are no co-products, no allocation is necessary in the studied system.

[1] https://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

3.7 Life cycle inventory

The life cycle inventory (LCI) is an inventory of input/output data that relates to the functional unit of the system being studied.

The foreground processes are based on activity data collected from project partners and literature. For this project, a data collection file was prepared and distributed to all partners in order to facilitate the data collection process. Primary data have been collected from WP 3-5 and WP 7-8 to date. The foreground data are described in detail in Section 4.

The LCI data describing background processes (e.g., electricity generation or natural gas production) are in large part from the ecoinvent database (version 3.3), a particularly robust and complete database, both in terms of technological and environmental coverage. This database can be used in ISO-compatible LCAs and it is internationally recognized by experts in the LCA field.

The quality of LCA results is dependent on the quality of data used in the study. Therefore it is necessary to utilize, research and implement the most credible and representative information available. Overall data quality will be further improved for the detailed LCA which will be delivered in M36.

The environmental LCA follows the main guidelines of the International Reference Life Cycle Data System (ILCD) Handbook and the ISO norms 14040-14044.

3.8 Environmental impact assessment

The life cycle impact assessment (LCIA) is the step in which the data on the quantities of emissions produced and resources consumed by the life cycle of a system is transformed into information on the damages caused to the environment. The impacts are calculated using characterization factors recommended in internationally-recognized impact assessment methods.

In the LCA of the hydrogen recovery systems developed within HyGrid, the IMPACT 2002+ (Humbert, De Schryver, Bengoa, Margni, & Jolliet, 2014) LCIA method is used for this task. The IMPACT 2002+ framework links the emissions caused and resources consumed by the life cycle of a system to five so-called endpoints (damage-oriented) categories (human health, ecosystem quality, climate change, resources, and water withdrawal). It was originally developed at the Swiss Federal Institute of Technology of Lausanne (EPFL), Switzerland. Subsequently, Quantis made some updates to the original IMPACT 2002+ methodology version 2.1[2]. This adapted version is referred to as "IMPACT 2002+ version Q2.27 (adapted by Quantis)". The life cycle assessment focuses on the five IMPACT 2002+ end-point indicators (described in **Table 2** below) over the entire lifecycle of the processes.

[2] The main difference between IMPACT 2002+ v2.1 and IMPACT 2002+ vQ2.2 (adapted by Quantis) are (i) climate change characterization factors are adapted with global warming potentials for a 100 year time horizon, (ii) water withdrawal, water consumption and water turbined are added as the midpoint categories, (iii) aquatic acidification, aquatic eutrophication and water turbined are brought to the damage category ecosystem quality, and (iv) normalization factors are updated.

Table 2: Description of IMPACT 2002+ endpoint indicators

Indicator	Definition
Greenhouse gas emissions	This indicator measures the potential impact on climate change from greenhouse gas emissions associated with a product, process or organization. It takes into account the midpoint category “global warming". The impact metric is expressed in kg CO_2-eq.
Resources depletion	This indicator measures the potential impact on resource depletion from resource use (e.g. fossil fuels and minerals) associated with a product, process or organization. It takes into account non-renewable energy and mineral extraction. These factors are simply the sum of the endpoint categories non-renewable energy consumption and mineral extraction. The impact metric is expressed in MJ ("measures the amount of energy extracted plus the amount needed to extract the resource itself").
Water withdrawal	This indicator measures the amount of water withdrawal associated with a product, process or organization. It takes into account water (whether it is evaporated, consumed or released again downstream) excluding turbined water (i.e., water flowing through hydropower generation). It considers drinking water, irrigation water and water for and in industrialized processes (including cooling water), fresh water and seawater. This indicator is actually based and expressed on volumes (m^3) of water withdrawal.
Human health	This indicator measures the potential impact on human health caused by emissions associated with a product, process or organization. It takes into account human toxicity (carcinogenic and non-carcinogenic), respiratory inorganics, ionizing radiation, ozone layer depletion and respiratory organics. It characterizes disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (rate of incidence of a disease). The impact metric is expressed in DALY (“disability-adjusted life years”).
Ecosystem quality	This indicator measures the potential impact on ecosystems (biodiversity, species and their inhabitant) caused by emissions or resource use associated with a product, process or organization. It takes into account aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification & nutrification, aquatic eutrophication, aquatic acidification, water turbined and land occupation. It characterizes the fraction of species disappeared on one m2 surface during one year. The impact metric is expressed in PDF.m^2.y (“potentially disappeared fraction of species over one m^2 and during one year”).

By means of an iterative approach, the preliminary LCA results will help identify the hotspots per indicator and provide recommendations on the most promising scenarios or configurations from a sustainability point of view, thus guiding eco-design of the HyGrid solution. This approach is key for partners to ensure that the developed solutions are indeed more environmentally friendly than the leading reference technology. As such, LCA can be used as a valuable decision-making tool for selecting and supporting the most favourable and/or promising technology from an environmental perspective as well as to raise awareness on the hotspots to address by project partners.

Partners have been made aware that should they struggle to make design decisions and environmental impacts could be relevant to consider, they should contact Quantis in order to guide the design towards the most sustainable solution.

Quantis will perform sensitivity analyses deemed relevant by project partners after the screening LCA has been submitted. The results of such assessments are useful for partners to understand the differences in different scenarios/configurations and to help partners to focus on hotspots that could yield overall improvements in terms of environmental impacts.

3.9 Life cycle costing assessment (LCC)

The HyGrid project will further investigate the latest advances in monetary valuation of impacts. The HyGrid framework is an interesting and challenging case for testing the combination of LCA and LCC. In order to ensure consistency between the two methods and to enhance the integrated evaluation of the investigated technologies and products, the LCA and LCC will have the same or equivalent data structure and system boundaries and will rely on the same data especially regarding the consumption of raw materials, energy and operating supplies.

A data collection file will be prepared and sent to partners after the delivery of the preliminary LCA results, to request the costs associated with each input and output of the system.

3.10 LCIA limitations

LCIA results present potential and not actual environmental impacts. They are relative expressions, which are not intended to predict the final impact or risk on the natural media or whether standards or safety margins are exceeded. Additionally, these categories do not cover all the environmental impacts associated with human activities. Impacts such as noise, odours, electromagnetic fields and others are not included in the present assessment. The methodological developments regarding such impacts are not sufficient to allow for their consideration within life cycle assessment. Other impacts, such as potential benefits or adverse effects on biodiversity, are also only partly covered by current impact categories.

3.11 Calculation tool

SimaPro 8.4 software, developed by PRé Consultants (www.pre.nl) was used to perform the LCA modelling and link the reference flows with the LCI database and link the LCI flows to the relevant characterization factors. The final LCI result was calculated combining foreground data (intermediate products and elementary flows) with generic datasets providing cradle-to-gate background elementary flows to create a complete inventory of the investigated systems.

4 LIFE CYCLE INVENTORY DATA

4.1 Data availability

Since HyGrid's consortium includes experts in all sub-systems of the hydrogen recovery systems, as far as possible project-specific primary data from project partners has been used, at least regarding the quantities of required input materials, energy and direct emissions occurring for the production and use phase. For the disposal phase, where higher uncertainties about the fate of components during disposal or recycling processes available in the future occur, it is necessary to rely on literature data and experts' feedback. Further, data on the environmental impacts of background processes such as general transport services, the production of the manufacturing infrastructure, the production of the required raw materials or the generation of the necessary fuels are taken from the environmental database ecoinvent. The various data sources used in the project are shown in **Figure 5**.

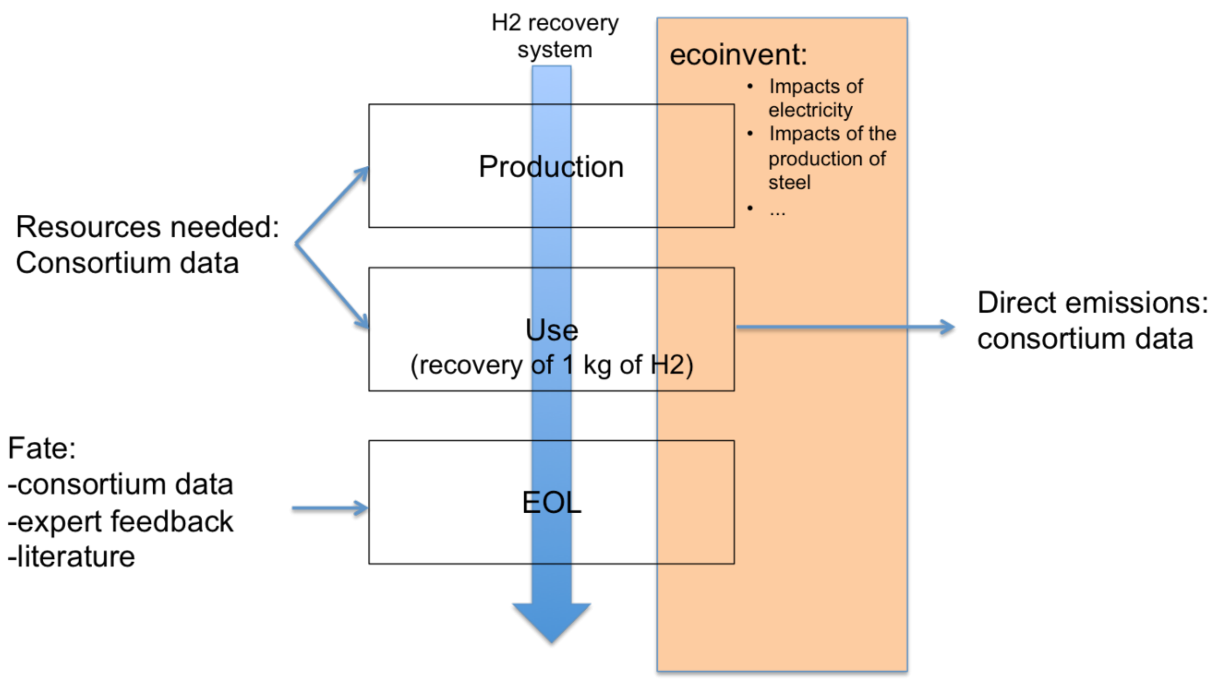

Figure 5: Key data sources used for the LCA.

The management of the data collection (including coordination, preparation of data collection templates, definition of a time plan, etc.) is key to the success of WP9, as data availability is key for Quantis to be able to perform the assessments. Quantis encourages interactive dialogue throughout the project, by means of regular actions, teleconferences and discussions during meetings.

4.2 Key assumptions

The main data and hypotheses used in this study are detailed below.

Electricity mix

The electricity mix used for all activities occurring in Europe is the "Electricity, low voltage {RER}| market group for | Alloc Rec, U" mix, representing the average electricity mix used in Western Europe through the highly interconnected electric grid. If the specific location of a process is known, the corresponding country mix was used.

Water balance

In the framework of this preliminary LCA, only the input of water is considered. For the final LCA, also the treatment and disposal as well as evaporation will be considered. The typical assumption is that 20% of the water evaporates while 80% is treated in a wastewater treatment plant (or according to the local technological standard).

Consumables

Consumables are material needs that have a much smaller lifetime than the overall system, such as lubricating oil. Here, no assumptions had to be made.

Infrastructure

No infrastructure is taken into account as the grid is necessary for both the PSA (reference system) and the HyGrid technology. Thus it is solely for the purpose of a comparison.

Transport

Specific transports are included where data was provided. Otherwise, standardized transport is included where relevant.

4.3 Key data

Table 3: Key data

	Original prototype[1)]	Configuration 16[1)]	PSA[2)]
H2 produced	25 kg/day	12.5 kg/day	25 kg/day
Electricity use phase	3.27 kWh/kg H2	4.23 kWh/kg H2	27.43 kWh/kg H2
Heat use phase	TBD	TBD	3 kWh/kg H2
Overall weight of system[3)]	~3 t	~3 t	100 kg
Main materials	Steel	Steel	Steel

[1)] All data used for modelling is based on the data received during the data collection period in March – April 2018. Not yet the overall system, but only the sum of the single components (without casing and tubing) is included yet. Changes, especially in terms of overall weight, are to be expected for the final LCA.

[2)] Please note that it was decided that the PSA would be an inappropriate reference system after all, as it is unclear whether or not it could operate at similar conditions as the HyGrid system. For the final LCA, an alternative reference system will be defined.

3) As mentioned in 1), the weight for the HyGrid system was calculated by summing up the data given by the individual WPs and does exclude all casing and tubing. For the final LCA, these numbers will be updated and the full plant will be considered. For the PSA (i.e. reference case), the weight was indicated by WP2. In case the PSA will remain the reference case, a consensus has to be reached within the consortium as the exact weight is rather controversial. In order to have a conservative approach for this comparison between the HyGrid system and the reference system, we settled for the weight indicated by the respective WP. The approach is conservative in the sense that it does not make the environmental impacts of PSA unnecessarily high, as a very light version with a few kg of steel is assumed. A sensitivity analysis revealed rather low sensitivity to the change in the overall weight of the system. If the demand in steel is 60-fold to the demand indicated in **Table 3** (which would increase the steel from 100kg to 6t)**,** the impact increases by 10% in the impact category for human health, 15 % in for the impact in the category climate change, and 28% for the demand in resources. In the impact categories of freshwater withdrawal as well as ecosystem quality, the change in impact was negligible. For the final LCA, a thorough assessment of the weight of the HyGrid system is intended. The final choice for the reference case has yet to be made.

5 RESULTS

This section presents preliminary LCIA results for the PSA reference case, the original prototype of the HyGrid system and the HyGrid system in its latest configuration (No. 16). The goal is to identify and understand the hotspots contributing to the overall comparative LCA results.

5.1 Overall comparison

Figure 6 shows the preliminary impact results of recovering 1 kg of hydrogen with two different HyGrid systems and with a theoretical PSA using the data as described in **Table 3**. Due to the multi-indicator approach, relative results are presented, which are normalized to the highest impact result for each impact category for each different system (see also **Table 4**).

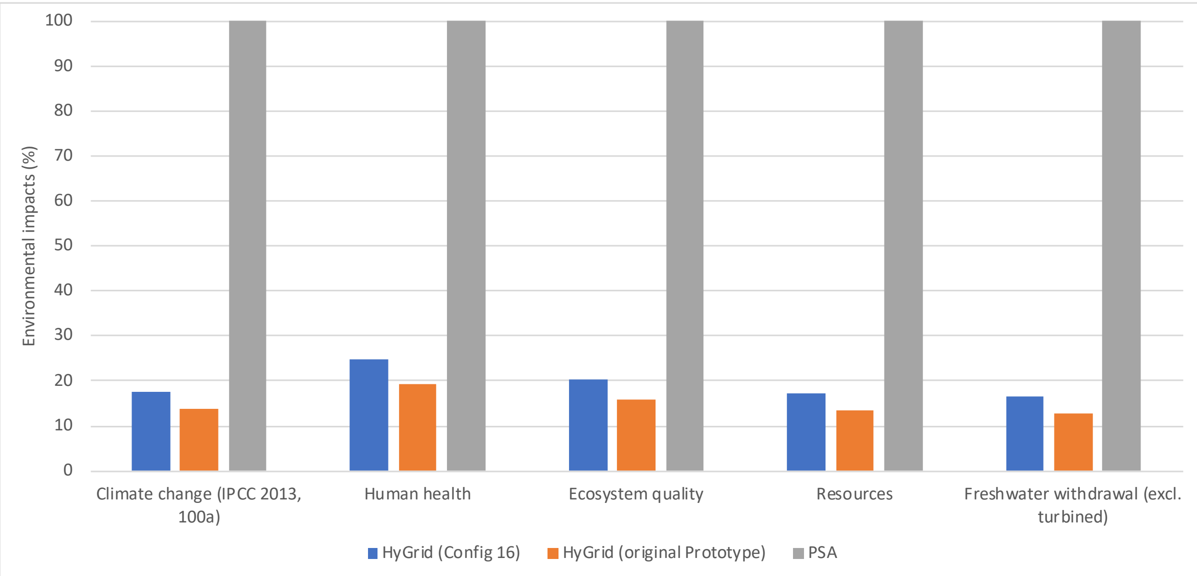

Figure 6: Life cycle impact results for recovering 1 kg of hydrogen using different technologies.

The preliminary results show that the PSA technology is most impacting for all indicators studied. It has to be noted that the PSA technology is expected to have an even higher impact in the final LCA when the entire infrastructure will be considered. This is expected to lead to a more pronounced difference between PSA and HyGrid with HyGrid performing even better comparatively. The least impacting option on all indicators appears to be the recovering of 1 kg of hydrogen using the HyGrid system as in the original prototype. The difference in the results between the two HyGrid systems is due to the fact that configuration 16 is less efficient in terms of material use per unit of output than the original prototype, as it works with the same components on a smaller feed flow and thus has higher requirements to recover the same amount of hydrogen.

Absolute values for each impact category as well as relative percentages for the preliminary results are provided in **Table 4** below for transparency.

Table 4: Life cycle impact results for the reference and the HyGrid technologies

		Characterized Results (unit based on indicator)			Relative Results (%)		
Impact Category		HyGrid (Configuration No. 16)	HyGrid (Original Prototype)	PSA	HyGrid (Configuration No. 16)	HyGrid (Original Prototype)	PSA
Climate change (IPCC 2013, 100a)	kg CO2-eq	2.61E+00	2.03E+00	1.48E+01	15	12	100
Human health	DALY	2.60E-06	2.04E-06	1.05E-05	23	18	100
Ecosystem quality	PDF.m2.y	1.59E+00	1.24E+00	7.84E+00	20	15	100
Resources	MJ	4.88E+01	3.79E+01	2.83E+02	13	10	100
Freshwater withdrawal (excl. turbined)	m3	3.43E-01	2.66E-01	2.08E+00	15	12	100

Note that heat demand of the HyGrid technology has not been included to date in this assessment because of ongoing developments in other WPs. They will be included in the updated results that will be presented at the M30 meeting. As we can see in chapter *5.2 Detailed Results: Contribution analysis*, the heat only makes a minor difference in the PSA case and most impact stems from electricity. When adding the heat consumption to the HyGrid technology, the difference between HyGrid and PSA will be reduced to an extent depending on the amount of heat needed.

5.2 Detailed results: Contribution analysis

Figure 7 presents the contributions on GHG emissions for the two HyGrid options as well as the reference case. It is distinguished between manufacturing and the use phase. The manufacturing includes all material and energy use for the construction of the systems. The use phase includes the energy used to run the systems. For all three options, the use phase clearly dominates the impacts.

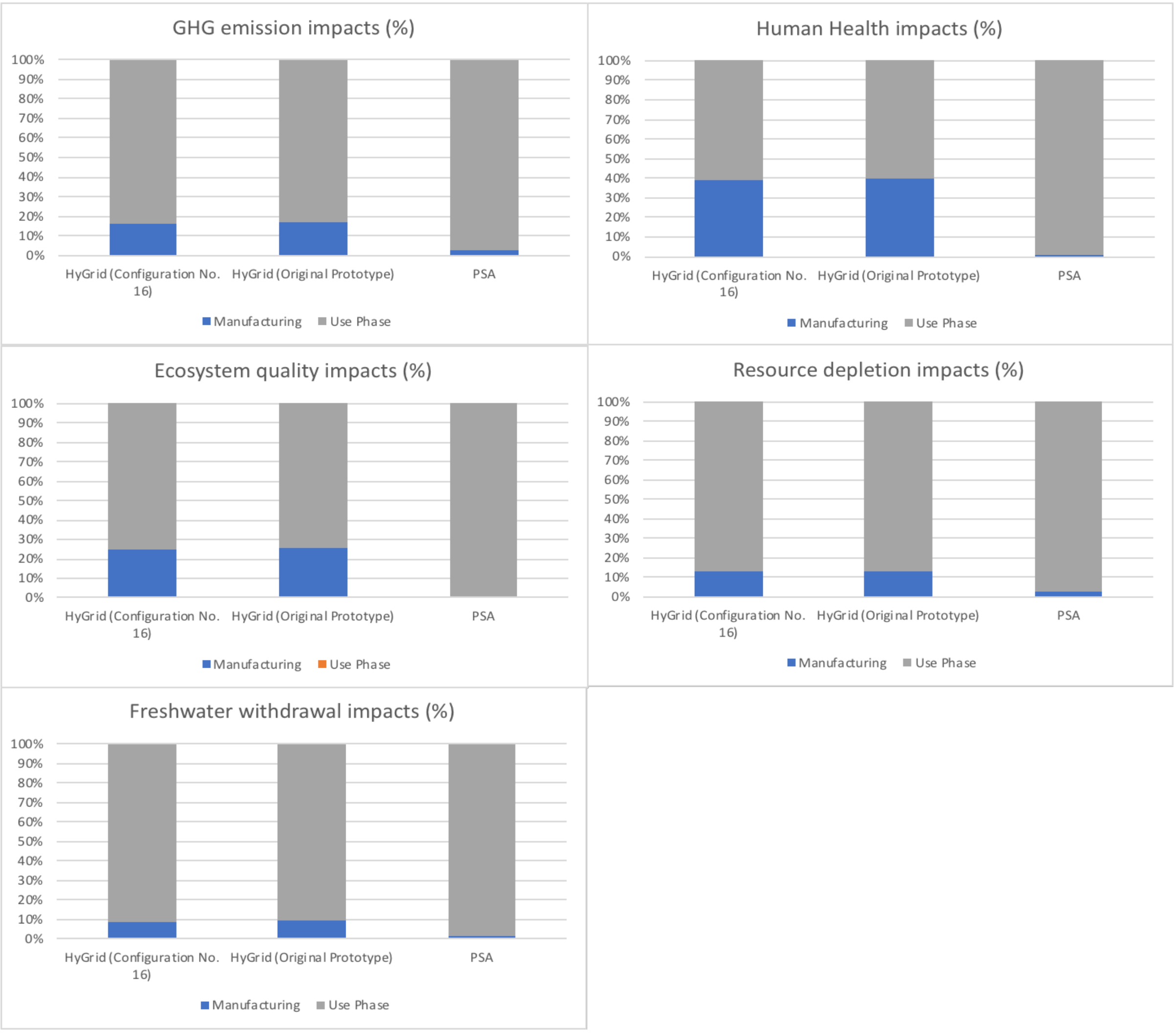

Figure 7: Contribution analysis for the two HyGrid options as well as the reference case for all impact categories (Figure 7.1. GHG emission impacts; Figure 7.2. Human Health impacts; Figure 7.3. Ecosystem quality impacts; Figure 7.4. Resource depletion impacts; Figure 7.5. Freshwater withdrawal impacts).

Main contributor for all impacts is the use phase, due the combustion of fossil fuels for the production of electricity used in the systems. The difference in electricity usage between PSA and the HyGrid systems is very high: for example HyGrid (Configuration 16) uses 86% less electricity than the PSA system. However, the share of the use phase varies depending on the indicator. In comparison, the impacts from the manufacturing phase is at 40% in the human health category while only 10-25% for the other categories. The relatively higher contribution to the impacts on human health is due to the mining activities associated with the metals used in the manufacturing process.

5.3 Analysis of HyGrid Configuration 16

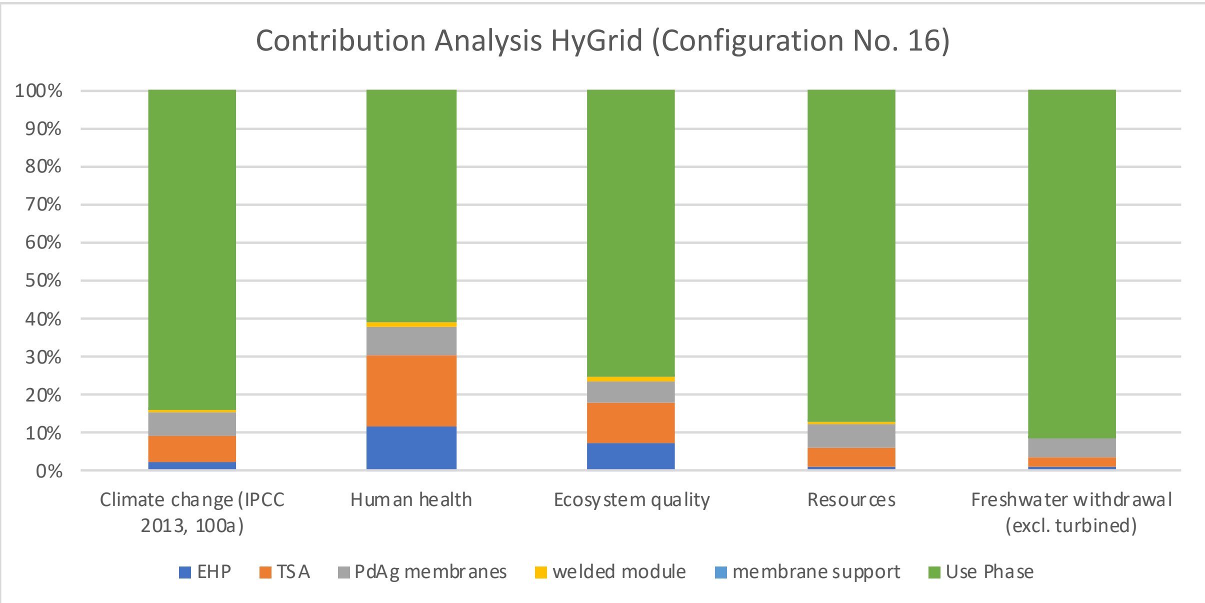

Figure 8: Contribution Analysis HyGrid (Configuration No. 16)

Figure 8 shows the contribution of the different components of the HyGrid system to the overall impact for each indicator. Electricity in the use phase dominates the impact for all indicators, as seen already in the previous section. The impact of the electricity mix in the category of climate change is mostly due to the burning of coal. For human health, the impact stems from various sources. Among the most relevant is again the coal, but also the in-situ leaching of uranium during mining operations and impacts from the electricity production from natural and coal gas. Ecosystem quality is compromised by all activities related to the production of conventional electricity such as off-shore drilling, coal and uranium mining. Resource depletion is increased by the mining of the mentioned raw materials. Water is used for cooling processes in the production of electricity. During this procedure, water evaporates and thus leads to a net freshwater withdrawal.

In order to get a more detailed view of the environmental impact of the manufacturing part only, the use phase is excluded in **Figure 9**.

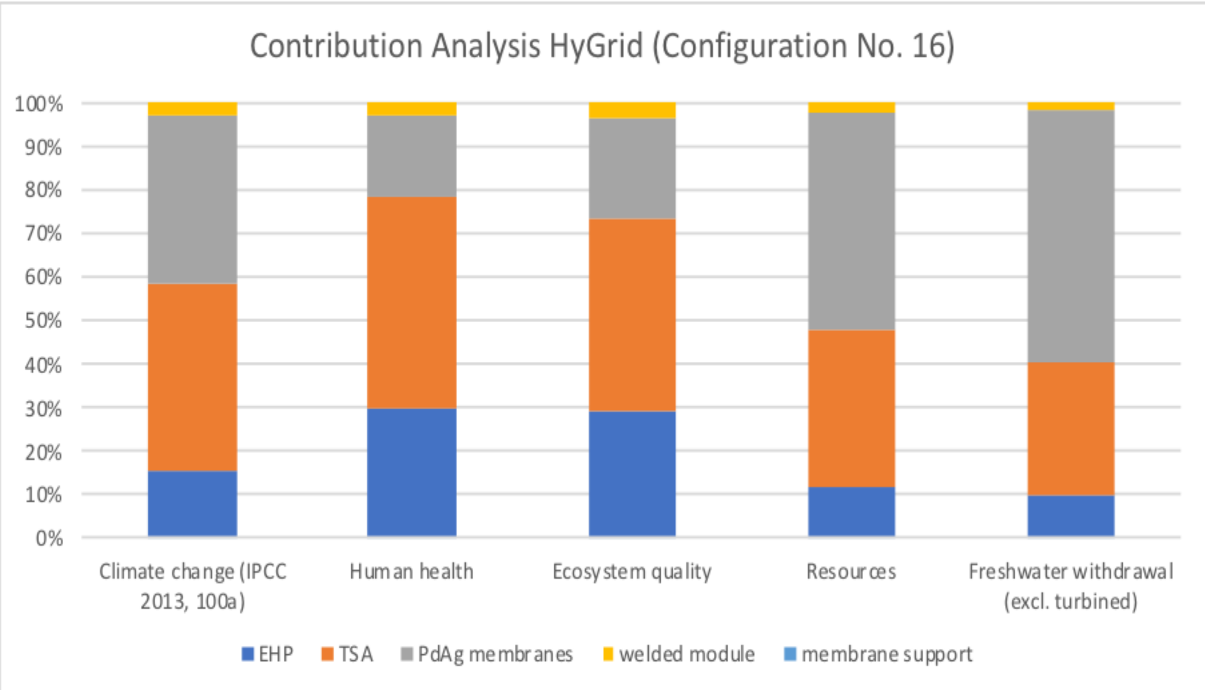

Figure 9: Contribution Analysis HyGrid (Configuration No. 16, manufacturing only).

Considering only the manufacturing phase of the HyGrid system (**Figure 9**), it is possible to get a more detailed view of the different components' contribution to the individual impact categories.

For **climate change**, it is the TSA that accounts for about half of the impacts. Looking at the processes that contribute most to the carbon footprint of the manufacturing phase, it is the etching of steel, the steel itself (used in both TSA and EHP) as well as the electricity used for the baking of the membranes that are most relevant.

Human health is most influenced by the mining activities associated with the metal demand, as well as the electricity production needed for the membrane and steel production. As the electricity is a mix stemming from different sources, there is also a certain amount produced from fossil sources, for example by burning coal.

The **ecosystem quality** is impacted by the use of chemicals utilized for the mining activities. Moreover, the copper used in the distribution network for electricity has also a negative effect on the ecosystem.

Resources are depleted namely because of the usage of fossil fuels for electricity production and the hard coal used for steel production.

The freshwater that is withdrawn is used mainly for cooling activities related to electricity production.

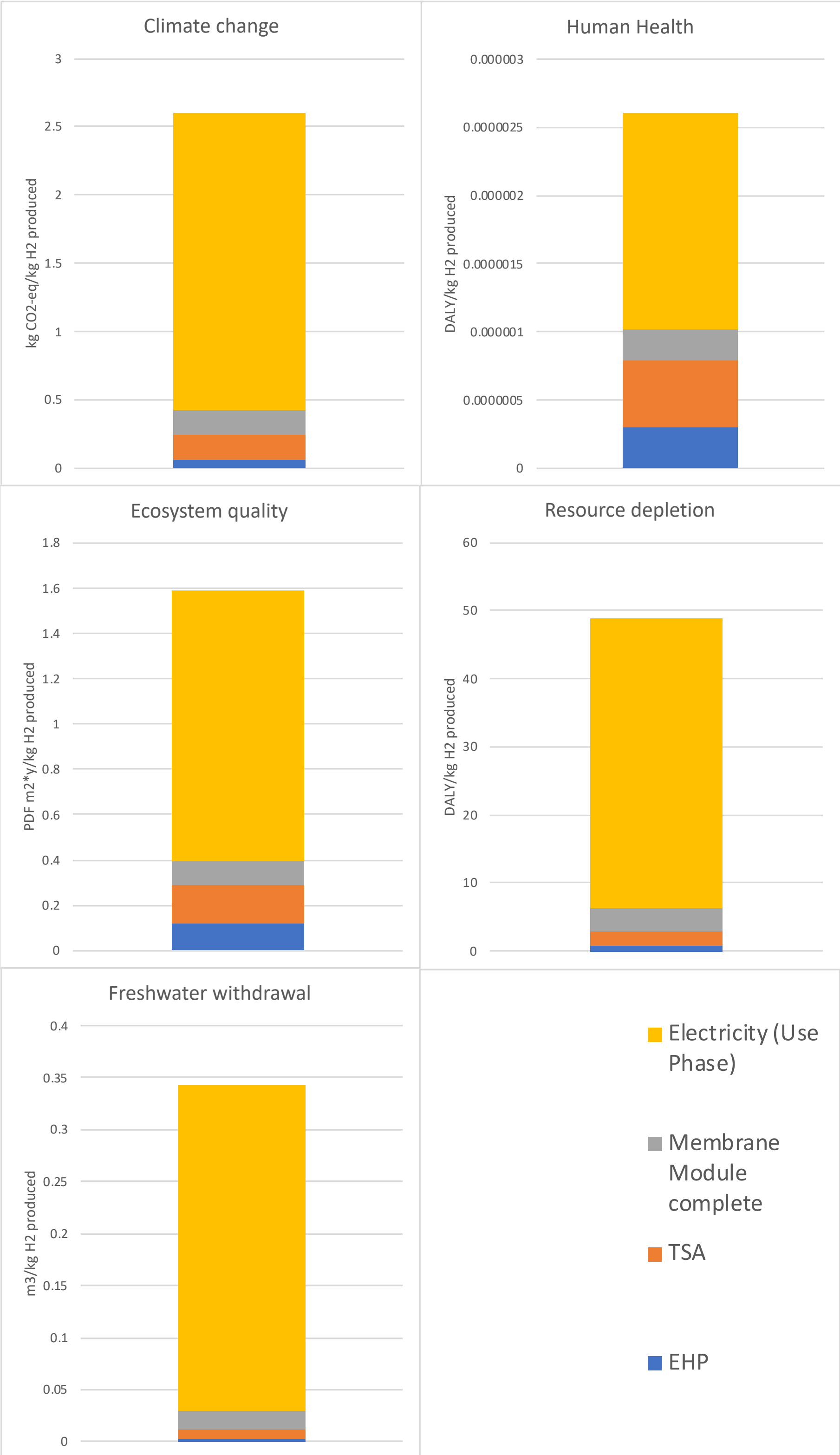

Figure 10: Results for each indicator in absolute values.

5.4 Study limitations

The LCA results presented here are limited to the objectives, goal and scope defined beforehand. This study is based on available primary data combined with generic data from existing commercial databases or best estimates. There are, therefore, some important limitations to the outcomes of this study. The main limitations include the following:

- Unlike environmental risk assessment conducted in a regulatory context, which uses a conservative approach, LCA seeks to provide the best possible estimate (Udo de Haes et al. 2002). In other words, the LCIA tries to represent the most probable cause in that the models (of transport and fate of contaminants in the environment and toxic effects on biological receptors) do not attempt to maximize exposure and environmental damage, the worst case scenario approach.
- This study is an attributional LCA study, not a consequential LCA. In short, it focuses only the environmentally relevant flows to and from the systems studied, and not on any marginal perturbations of those flows as a result of changes in the life cycle (Ekvall & Weidema, 2004).
- LCIA methodologies such as IMPACT 2002+ do not and cannot characterize the wide array of emissions released to soil, air and water from processes. However, it does characterize the most well-known pollutants and in doing such, provides the best estimate to evaluate environmental impact.
- LCIA results present potential and not actual environmental impacts. They are relative expressions, which do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks. Additionally, these categories do not cover all the environmental impacts associated with human activities. Impacts such as noise, odours, electromagnetic fields and others are not included in the present assessment. The methodological developments regarding such impacts are not sufficient to allow for their consideration within

life cycle assessment. Other impacts, such as potential benefits or adverse effects on biodiversity, are also only partly covered by current impact categories.

When this study is communicated to stakeholders, the magnitude and nature of the limitations should be communicated at the same time.

6 CONCLUSION

The preliminary results show that the HyGrid technology is less impacting than the theoretical PSA system for all indicators that were analysed. However, this comparison has a limited validity as it is not possible to separate hydrogen from other gases with the PSA technology for the current case. However, at levels of more than 50% of hydrogen in methane, the PSA technology would work.

The most impacting phase of the HyGrid system is the use phase, where the electricity consumption accounts for a high share of the impacts for all indicators. The use phase might gain even more in importance when adding the heat consumption of the system. The impacts related to electricity are mainly due to the combustion of fossil fuels for the production of electricity, as the European electricity mix is based for a great share on fossil fuels.

The impacts from the manufacture of the HyGrid system are due for a high share to the use of steel in the TSA and the EHP. The fabrication of the membranes uses a lot of electricity during the baking of the membrane in the oven at high temperatures, which account for most of the impacts of this part. Overall, impacts are dominated by the electricity consumption in the use phase and the use of steel and other metals in the manufacturing process.

It is important to note that, rather than measuring direct measurements of real impacts, LCA estimates relative, potential impacts and that results and conclusions should be considered applicable only within the scope of the study.

A more detailed final environmental LCA will follow and build upon the screening environmental LCA, aiming at providing a complete LCA of the investigated HyGrid system. Especially, it is expected that more detailed data on all processes will be available and therefore integrated. This goes for example for transport ways and material processes. Furthermore, the overall casing and potential supplementary machinery will be implemented.

The reference system is expected to be adapted. Several comments have been raised about the suitability of the PSA for the required task. An alternative scenario will be developed or the current scenario will be altered to provide a meaningful reference system.