DELIVERABLE D5.4

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Environmental performance analysis

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Abstract: Tecnalia will evaluate the environmental impact of the hydrogen plant in the actual deployment and in the case studies identified in task 5.2. The evaluation will include field experience from VK and data gathered by KES. Tecnalia will conduct a Life-Cycle Assessment with a gate-to-gate perspective. This assessment takes the operation of the plant as the system to analyse, taking into account the activities needed to operate and maintain the plant during the demonstration run in WP8 in each tested operating mode. The LCA will be in line with international standards, such as ISO 14044 and ILCD Handbook. Tecnalia will build a representative Life Cycle Inventory, collecting the necessary information from VK and NEL. Tecnalia will gather information regarding energy consumption, auxiliary materials, water consumption and waste generated during the operation of the plant. The environmental impact will be evaluated using actual and widespread characterization methods, such as CML, ReCiPe, ILCD Midpoint, etc. Several impact categories will be taken into account, including Climate Change, Ozone Layer Depletion, Photochemical Oxidation, Acidification Potential, Eutrophication Potential and Resource and Fossil Fuels Depletion. Tecnalia will interpret the results towards the identification of the system's environmental hotspots and enhancing decision making.

Revision History

Date	Description	Author
2023/Jan/24	Initial draft version	Jorge Arnal, Marina Isasa (Tecnalia)
2023/Mar/04	Comments and suggestions to improve the document (QA)	Luigi Glielmo (UniSannio)
2023/Mar/07	Final version including QA suggestions	Jorge Arnal (Tecnalia)

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Acronyms

ADP: Abiotic Depletion Potential.

AP: Acidification Potential.

ELCD: European Life Cycle Database.

EP: Eutrophication Potential.

ES: Spain.

EU: European Union.

FAETP: Freshwater Aquatic Eco-Toxicity Potential.

GHG: Greenhouse Gases.

GLO: Global.

GWP: Global Warming Potential.

HTP: Human Toxicity Potential.

ILCD: International Reference Life Cycle Data System.

ISO: International Organization for Standardization.

JRC: European Commission Joint Research Centre.

LCA: Life Cycle Assessment.

LCI: Life Cycle Inventory.

LCIA: Life Cycle Impact Assessment.

MAETP: Marine Aquatic Eco-Toxicity Potential.

NO: Norway.

ODP: Ozone layer Depletion Potential.

PEF: Product Environmental Footprint.

PEM: Proton Exchange Membrane.

POCP: Photochemical Ozone Creation Potential.

RES: Renewable Energy System.

RO: Reverse Osmosis.

TETP: Terrestrial Eco-Toxicity Potential.

WP: Work Package.

1 Introduction

Considering the importance of developing renewable energy sources to meet future energy demand and, at the same time, support the transition of European economic growth away from fossil fuels and thus mitigate climate change, different renewable energy technologies and innovations are being currently developed. Of all these technologies, those for H_2 production are among the most promising alternatives to reduce the use of traditional fossil fuels. However, it is estimated that around 96% of the H_2 produced today comes from fossil fuels [1], and more than 50% of the total H_2 is still produced by steam methane reforming (SMR) which, although currently presented as the cheapest method of producing H_2, does not avoid the problem of CO_2 emissions [2]. In this sense, combining the use of renewable energies with electrolysis processes to produce hydrogen significantly reduces CO_2 emissions from the process and, at the same time, boosts H_2 production [3].

In this context, this deliverable has been prepared in the framework of the European project HAEOLUS. HAEOLUS is an EU co-funded project that proposes the integration of a new-generation electrolyser in the remote region of Varanger, Norway, inside the Raggovidda wind farm, whose growth is limited by grid bottlenecks. Besides, the project aims at demonstrating different control strategies to enhance the techno-economic performance of the system, considering different operating configurations (energy storage, mini-grid, fuel production). In addition to H_2 production, the project aims to demonstrate the use of a 2.5 MW PEM electrolyser and a 120 kW fuel cell, limited to 100 kW due to regulatory restrictions, for re-electrification, with a target cost for the electrolyser of 3 M€/(tonne/day).

The above-mentioned performance has been tested in the different work packages of the HAEOLUS project and, specifically, in *WP5 – System Integration,* whose objective is, on the one hand, to analyse the environmental impacts of the wind-hydrogen integrated systems, providing solutions for minimizing the environmental burdens of the identified hotspots, and on the other hand, to evaluate the applicability of the system design in different operating conditions. All these actions lead to the definition of a strategy to overcome possible obstacles encountered in the development and implementation of the project technology in order to improve its performance in the future.

To this end, this report focuses on the environmental impacts' analysis of the project technologies. It presents the results of the Life Cycle Assessment (LCA) carried out to determine the environmental impacts and possible critical points of the innovations developed in the framework of the HAEOLUS project. The chosen methodology follows the International general standards on LCA, namely: ISO 14040:2006 and ISO 14044:2006. According to ISO 14040:2016, the procedure for carrying out an LCA consists of the compilation of relevant inputs and outputs of a product system, the evaluation of the potential environmental impacts of the relevant inputs and outputs, and the interpretation of the results.

In terms of data collection, and in order to ensure a consistent environmental analysis, the results of the project tests and other feedback from the project partners have been taken into account in the current deliverable. In addition, data from other specialised sources on H_2 production and wind energy integration has been considered. This data collection has been the basis for the definition of the inventory analysis, where raw materials, energy and waste flows associated to the operation of the HAEOLUS system have been identified and quantified. Subsequently, potential environmental impacts have been evaluated, to conclude with the interpretation of the results, where the assessments of selected technologies are presented.

1.1 Document content description

In line with the content of this introductory section, this report is structured as follows: Section 1 corresponds to this introduction and the contextualisation of the analysis, section 2 describes the general aspects of the Life Cycle Assessment and the considered methodological approach, section 3 analyses the goal and scope of the study, section 4 presents the LCI of this study, including a detailed explanation of the components that make up the system under study, section 5 contains a summary of the life cycle impact assessment (LCIA) and the interpretation of the obtained results and section 6 contains the most significant conclusions obtained after the analysis.

2 Life Cycle Assessment. Methodological approach

Life Cycle Assessment (LCA) is a methodology for assessing the environmental impact of a product, process or service throughout its life cycle. LCA can identify energy and material use and waste released into the environment, as well as the evaluation and implementation of improvement opportunities. The LCA methodology used in this deliverable is based on the following two standards:

- ✓ ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework (ISO, 2006a) [4].
- ✓ ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines (ISO, 2006b) [5].

Life cycle assessments can be used as a product or process design improvement tool, helping designers and engineers to identify environmental factors attributable to specific materials or life cycle stages, ultimately enabling informed and robust decisions and improvements to be made. LCA is also of interest to potential investors and energy and government authorities, who can consider the environmental implications of the product before investing in or commissioning such a project.

According to the ISO 14040, there are 4 different phases to conduct a LCA study:

1. **The goal and scope definition phase:** In this phase, the reasons for carrying out the study (goal) and the product system (scope) are defined. For this purpose, whether the results are used for comparative reasons or not, the intended audience, functional unit (reference to which the inputs and outputs are related), system boundaries (unit processes to be included in the system considering all life cycle stages), allocation procedures, impact categories, as well as system assumptions, need to be determined.
2. **The inventory analysis phase:** This phase involves collecting data (at all life cycle stages) and determining calculation procedures to quantify the most relevant inputs and outputs of a system. The data to be considered are inputs of raw materials and energy, products/co-products, waste and emissions, and should be related to the unit processes and the reference flow of the functional unit. The collected data must be validated.
3. **The impact assessment phase:** The purpose of this phase is to assess the environmental impacts taking into account the data collected during the inventory analysis phase. To this aim, the inventory data must be associated with the environmental impact categories and indicators. The mandatory steps within this phase are:
    - Selection of impact categories, category indicators and characterization models.
    - Assignment of LCI results.
    - Calculation of category indicator results (characterization).

   According to ISO, the optional phases are: normalization, grouping and weighthing of results. If necessary, the goal and scope of the entire analysis can be updated during this phase.
4. **The interpretation phase:** This phase presents the results consistent with the previously defined objective and scope. The aim is to generate a set of conclusions and recommendations for decision-makers.

Figure 1 shows how the different phases of LCA interact with each other.

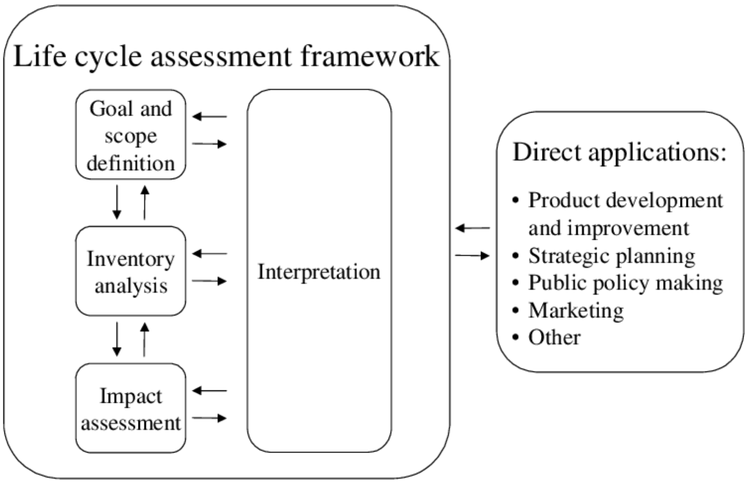

Figure 1. Stages of a Life Cycle Assessment (ISO 14040)

3 Goal and scope definition of the study

The goal of the LCA presented in this deliverable is to assess the environmental impact of the operation and maintenance (O&M) of the technologies developed in the HAEOLUS project. For this purpose, this study analyses the environmental impact associated with the hydrogen production through water electrolysis, using the electricity generated from a wind power plant located in Raggovidda.

In this regard, the specific objectives of this study are:

- Conduct an LCA of the production of hydrogen from wind energy in Raggovidda wind farm (wind-H_2-FC), considering all the project unit operations and different operating modes.
- Compare the previous LCA results with other fossil fuel-based hydrogen production processes and with the production of H_2 in other 2 case studies: Smøla(wind-H_2) and Moncayuelo (wind-H_2).
- Identify environmental hotspots in the system and potential points for improvement.

3.1 Reasons for carrying out the study and intended applications

The main reason for conducting this LCA is the need to meet the objectives previously mentioned. Furthermore, it must be taken into account that these technologies might be further developed in future projects, so another reason for carrying out the study is to identify the main critical environmental points in the O&M of each technology, so that these wind-H_2 systems can be optimised to reduce their environmental impacts. For this reason, a section focused on the interpretation of the results for each scenario evaluated has been included in the evaluation section.

3.2 Target audience

The status of this deliverable is public. Therefore, the main target audience are, apart from the partners of the HAEOLUS project and the European Commission, other interested stakeholders (from owners/operators of wind-hydrogen facilities, hydrogen technology providers, renewable energy providers or research institutes, to hydrogen end-users such as public authorities).

3.3 Functional unit

The functional unit represents the function of the product/process or service and must be consistent with the goal and the scope of the study. In this study, two different functional units have been used depending on the scenario considered and the use of the hydrogen generated in the electrolysis.

The first functional unit (FU) used this study is defined as **1 kWh of net electricity** generated through a wind-hydrogen-fuel cell integrated system. This FU is considered for those case studies where the H_2 generated is subsequently consumed in a fuel cell to generate electricity again. All emissions, materials and energy consumptions are referred to this FU.

Alternatively, another FU is also considered: **1 kg of hydrogen ready to be delivered**. This alternative FU is defined to facilitate comparisons with the other case studies within the HAEOLUS project, where the final product of the system is the hydrogen itself.

3.4 System boundaries

The system boundaries (SB) encompass all the processes necessary to provide the FU of the system. In other words, SB indicate what is and is not included in the analysis. Figure 2 shows the main life cycle phases and system boundaries examined in this study.

Figure 2. Life cycle stages for wind-H_2 systems included within the LCA boundaries

Focusing the study on the operation and maintenance stages of the system, the boundaries of the integrated Wind-H_2 system are shown in Figure 3. In this regard, the main operation units studied are:

- The electrolyser to produce hydrogen through water electrolysis by wind-electricity.
- The hydrogen compression and storage tank.
- The fuel cell for re-electrification.

For the quantification of the environmental impacts, a "gate-to-gate" approach has been applied, including only inputs (materials and energy) and outputs (products, emissions and wastes) for the operation and maintenance stages. The analysis of the manufacturing, transport, dismantling and scrapping phases of each operating unit is not included in this LCA. The transport of labor required for the operation and maintenance of the installation is also not included.

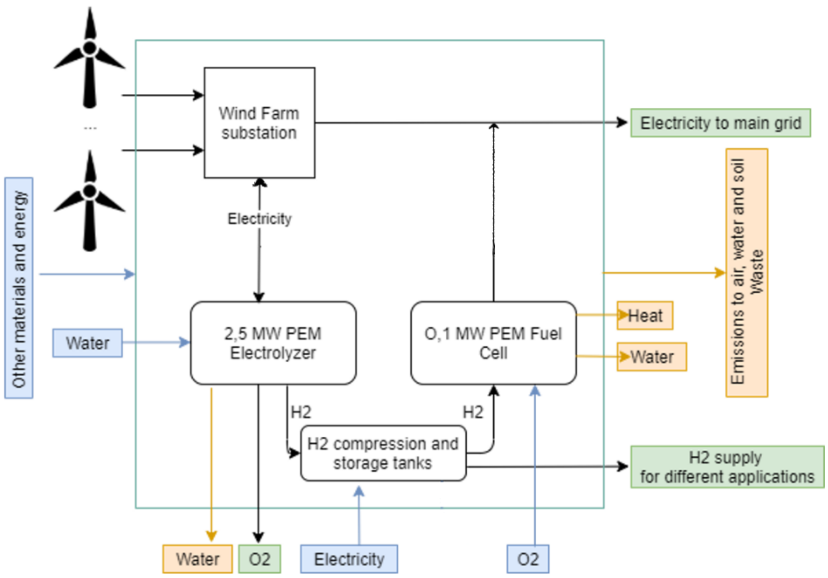

Figure 3. Wind-H_2 integrated system installed at Raggovidda

In this analysis, the LCA analyses all incoming and outgoing materials and processes required for O&M activities over the 20-year (natural lifetime) of the installation. Besides, the analysis considers results from the pilot plant installed at Raggovidda, as well as simulations performed for the other locations such as Smøla and Moncayuelo.

Physically, the system boundary reaches the end of the installation's power cable, with all downstream elements of the electricity transmission system outside the scope of this study, and/or to the point when the H_2 is ready to be delivered.

In addition to the above, the following boundaries have been considered:

3.4.1 Geographical boundaries

The results are representative for the corresponding geographical areas. In this sense, the H_2 generated at the Raggovidda and Smøla wind farms will be mainly destined to the Norwegian market, while the H_2 generated at Moncayuelo will be sold on the Spanish market. In case the H_2 is re-electrified, it has been considered that the impacts of the generated electricity should be compared with the electricity mix of each of these countries. Other LCA studies carried out in different countries or regions may be not comparable to the results obtained in this study.

3.4.2 Temporal boundaries

Since the installation and commissioning of the HAELOUS system took place in summer 2021, the data collection period was between September 2021 and March 2022, taking this period as representative of the operation and maintenance of the system. In fact, most of the data used for this report was collected in the second half of 2022. Other LCA studies conducted in different time frames may not be comparable to the results obtained in this study.

3.4.3 Technological boundaries

The HAEOLUS project aims at installing a PEM electrolyser, developed by CUMMINS with a capacity of 2.5 MW, at the Raggovidda wind farm, in Norway. The permitted utilization of the electrolyser ranges from 10 to 100% of its capacity.

The electrolyser is integrated with the wind farm, a hydrogen storage tank, and a 120 kW fuel cell for re-electrification. To maximize the relevance to wind farms across the EU and the world, the plant operates in multiple emulated configurations (energy storage, mini-grid, fuel production). On this basis, the processes within the system boundaries have been modelled from data provided by the project partners and/or based on relevant life cycle inventory databases, such as EcoInvent v3.7 and state-of-the-art technologies.

3.5 Cut-off criteria

The cut-off criteria specify the amount of material, energy flow or level of environmental significance associated with the product system that will be excluded from the study, being negligible to some extent. This must be defined clearly.

The cut-off criteria have been defined in accordance with PEF guidelines [6]. Only material inputs constituting all together less than 5% of the total mass of the components or processes within the scope can be excluded from the system boundaries, as long as the modelled flows account for at least 90% of the overall contribution to each of the environmental impact categories considered.

In this sense, to ensure a comprehensive analysis of the environmental performance of this technology, the material and energy inputs excluded from this analysis do not represent more than 3%

of the cumulative mass of the core system. This cut-off criterion is in line with the recommendations given by the EC in the PEF methodology.

3.6 Allocation procedures

The allocation rules deal with multifunctionality and the impact categories that must be calculated during the impact evaluation phase later in the study.

In this study, hydrogen is assumed to be the only product of the electrolytic conversion of water. Although it is likely that the environmental performance of electrolytic hydrogen would be improved if the co-produced oxygen could also be used, this is not considered feasible at the pilot scale considered in this study. Therefore, the oxygen produced is included as an emission to the atmosphere rather than a co-product and, as such, no allocation procedure is required.

3.7 Data-quality assessment

Based on the source of the data, the information included in the LCI can be classified into three categories [7]:

- Specific data (or primary data): data gathered from the actual manufacturing plant where product-specific processes are carried out and data from other parts of the life cycle traced to the specific product system under study.
- Generic data (or secondary data), divided into:
    - selected generic data – data from commonly available data sources (e.g., commercial databases and free databases) that fulfil prescribed data quality characteristics for precision and completeness.
    - proxy data – data from commonly available data sources (e.g., commercial databases and free databases) that do not fulfil all the data quality characteristics of “selected generic data”.

As a rule, specific data shall always be used, if available. If specific data is not available, generic data may be used, but they must be as representative as possible.

3.8 Selected impact categories

The selection of impact categories and characterization methods should be coherent with the goal and scope, so that the results obtained should answer the questions that motivated the analysis. In this sense, the ISO 14040:2016 recommends employing categories and methods which are internationally accepted, scientifically and technically valid and environmentally relevant, trying to harmonize this kind of analysis.

For this reason, this LCA study has been carried out taking into account the quantification of the environmental indicators proposed by the CML-IA assessment method, which is an internationally recognised method of analysis developed by the University of Leiden in the Netherlands. All the impact categories included in this methodology were initially selected for this analysis. However, it should be noted that given the difficulty of interpreting and communicating the results when many impact categories are analysed and given that the standard states that the categories can also be selected based on scientific publications results, only the most significant impact categories for the HAEOLUS project technologies were selected to be discussed in detail.

Some of the most relevant impact categories included in the CML-IA method are:

- Global warming potential (GWP): The global warming potential quantifies the contribution of gaseous emissions from the wind-hydrogen production systems to the environmental problem of climate change.

- Abiotic depletion potential (ADP): Fossil fuels, metals, and minerals are used in H_2 production systems. The abiotic depletion potential is an impact category that measures the use of these non-renewable resources.

- Eutrophication potential (EP): systems produce compounds that can cause eutrophication. Eutrophication occurs when surplus nutrients, mainly phosphorus (P) and nitrogen (N), are released into the environment.

- Acidification potential (AP): wind-hydrogen systems can produce compounds that cause acidification. Acidification is a process that occurs in the atmosphere when substances such as SOx, NOx and NH_3 react with water vapor to form acids. These acids reach the earth surface in form of acid rains which have damaging effect on fauna, flora, soils and buildings. In the CML-IA method, the acidification impact is expressed in mass equivalents of SO_2 released.

- Ozone layer depletion potential (ODP): Nitrous oxide is an important atmospheric trace gas contributing to both global warming and the depletion of the stratospheric ozone layer. The emission of harmful gas to the stratospheric ozone layer causes ODP.

- Photochemical Ozone Creation Potential (POCP): Impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manufactured materials through reaction with organic materials.

- Human toxicity potential (HTP): Impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion or penetration through the skin.

- Marine aquatic eco-toxicity potential (MAETP), terrestrial eco-toxicity potential (TETP) and freshwater aquatic eco-toxicity potential (FAETP): Ecotoxicity refers to the capability of a compound or any physical agent to show the harmful effect on both environment and organisms. These indicators consider damage caused to the marine, terrestrial and freshwater aquatic environments respectively.

3.9 Software and databases

In addition to the internal databases developed from data collected throughout the project from the partners and their specific processes, other existing databases and bibliographic data were used to support and complete the analysis when no experimental or site-specific data were available. In addition, SIMAPRO software was used to run the simulations and perform the calculations. More information about this software and existing databases used is:

SIMAPRO. This software is a flexible and well-designed tool for LCA studies based on ISO 14040, capable of simulating complex parametric models in different scenarios and calculating sensitivity analyses and statistical analyses. The current LCA has been carried out using the version v9.2.0.1.

ECOINVENT database: developed by the ETH (Swiss Research Institute). It contains information and emission factors for processes related to energy generation, extraction of mineral resources and basic industrial processes, waste treatment and transport, among others. As far as possible, the project has used the data available in the latest version of the EcoInvent 3.7 database (www.ecoinvent.org), in "allocation " mode (each transformation has an assigned impact). As already mentioned, this database partially supports and complements the actual data provided by the partners on the input and output of the current processes analysed in the HAEOLUS project.

4 Life Cycle Inventory

Life Cycle Inventory preparation is the phase of the LCA that involves the collection of all values related to the inputs and outputs of material and energy flows throughout the entire life cycle of a product. To facilitate its understanding and to have a global vision of the components involved in the life cycle of a product, the inventory is usually broken down by studying each of the phases that make up the scope of the analysis.

4.1 Data collection procedures

Two types of data were considered for the elaboration of the Life Cycle Inventory: primary data, which was obtained from the first-hand information provided by the HAEOLUS project partners, and which refer to the processes in which the partners have direct involvement or control, and secondary data, relating to the upstream and downstream processes to the central phase of the analysis. The consideration of secondary data allows not losing the life cycle perspective and the information necessary for its consideration is normally taken from specialised databases such as the European Life Cycle Database version (ELCD) or EcoInvent.

In this case, since the analysis has been done under a gate-to-gate approach, the information contained in the Life Cycle Inventory consists of concepts such as:

- Energy consumption (electrolyser, fuel cell, H_2 compression, etc.).
- Energy losses.
- Waste consumption.
- Auxiliary materials needed for the maintenance of the electrolyser + fuel cell.
- Useful lifespan of the main components.
- Productivity.
- The power of the electrolyser.
- Wastes generated during operation-maintenance activities.
- Other relevant data.

In this study, most of the inventory data was provided by the project partners or estimated by TECNALIA and subsequently validated by the project partners. Another important source of data collection has been the deliverables published earlier in the project, especially the project deliverables 5.3, 8.1, 8.2 and 8.3 [8]–[11].

The information from the project partners needed to compile the Life Cycle Inventory has been collected by means of questionnaires elaborated taking into account the scope defined in the previous chapter. An example of the type of questionnaire used is shown in Figure 4.

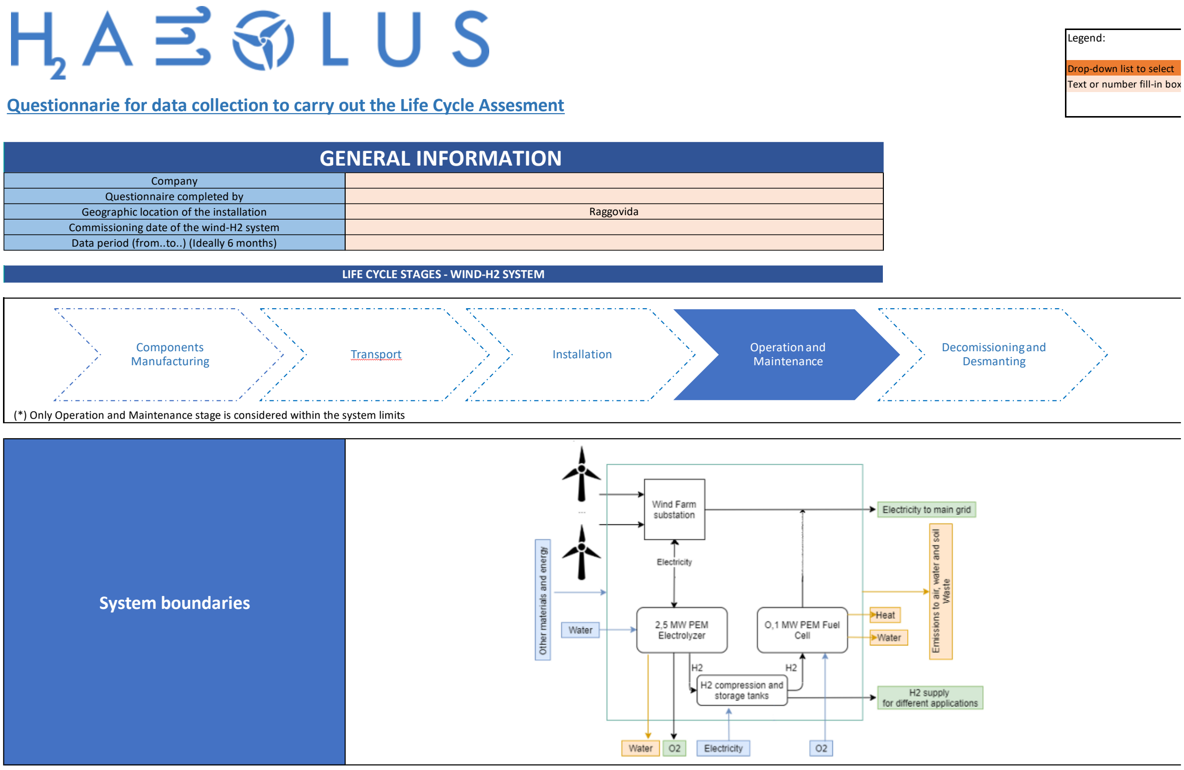

Figure 4. Questionnaire for data collection (screenshot)

4.2 Reference Model of the Wind-Hydrogen Integrated System (Wind-H_2)

The integrated Wind-H_2 system considered in the project consists mainly of five components, namely the wind farm, the substation, the electrolyser, the storage tank and the fuel cell. On the one hand, 3 different wind farms have been considered in the project. The Raggovidda wind farm is the main demonstration site of the project and real tests have been carried out in this location. On the other hand, the Smøla and Moncayuelo wind farms have also been theoretically considered as possible scenarios where to replicate the project technology.

4.2.1 Wind farms

Three different case studies of real wind farms in different working scenarios have been assessed by means of the LCA methodology: i) Raggovidda (wind-H_2-FC); ii) Smøla (wind-H_2) and (iii) Moncayuelo (wind-H_2). In the Raggovidda wind farm, the incorporation of the electrolyser, the H_2 storage tank and the fuel cell has been considered. In the other two plants, only the incorporation of the electrolyser has been studied.

The main characteristics of each of these wind farms are set out below. The information contained in this section has been obtained mainly from other deliverables previously published in the framework of the project (D5.3, D8.1, D8.2 and D8.3) [8]–[11].

4.2.1.1 Raggovidda

Raggovidda wind farm is located in the region of Varanger, Norway and consists of 15 Siemens Wind turbines, class IEC IA (3 MW, diameter 101 m) with a total nominal power of 45 MW. The technical specifications of the Raggovidda wind farm are presented in Figure 5 and Table 1. With an average capacity factor of 48.39%, the total electric power generation of the plant is about 190 GWh/ y. The described wind farm was inaugurated in 2014. Currently, there are two additional projects to increase the number of turbines in the wind farm and increase the energy produced in the area around Varanger.

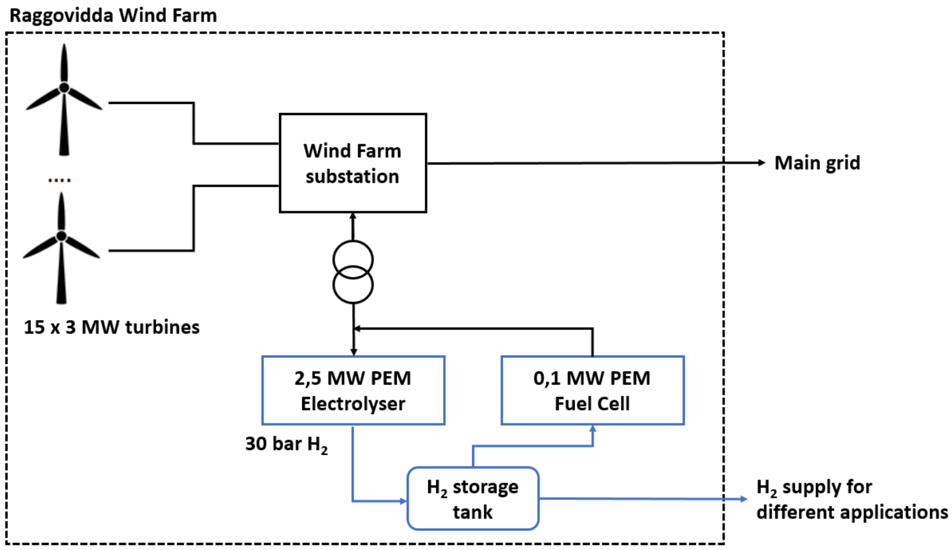

Figure 5. Conceptual layout of the Raggovidda Wind-H_2 system.

Table 1. Raggovidda Wind farm. System Specifications

WIND-H_2 System Specifications		
Parameter	**Value**	**Unit**
Wind-H_2 expected lifetime (global installation)	20	years
Wind farm installed power	45	MW
Number of wind turbines	15	units
Mean power	21.77	MW
Turbine nominal power	3	MW
Capacity factor (%)	48.39	%
Expected annual produced energy	190	GWh/year
Expected energy losses (due to equipment degradation)	2	%/year
Average wind velocity in the specific location	*9.8*	m/s

On the other hand, Table 2 summarises the results from the statistical study of the real generation of the Raggovidda wind farm for 2015, 2016 and 2017. Regarding the hourly generation profile, the histogram plotted in Figure 6 shows that the statistical distribution is very similar along the three years.

Table 2. Summary of Raggovidda wind farm generation 2015-2017.

Raggovidda wind farm Generation 2015-2017				
Year	**Max (MW)**	**Min (MW)**	**Mean (MW)**	**Generation (MWh)**
2015	45.35	0.00	22.46	196781
2016	45.18	0.00	20.85	182662
2017	45.03	0.00	21.78	190762

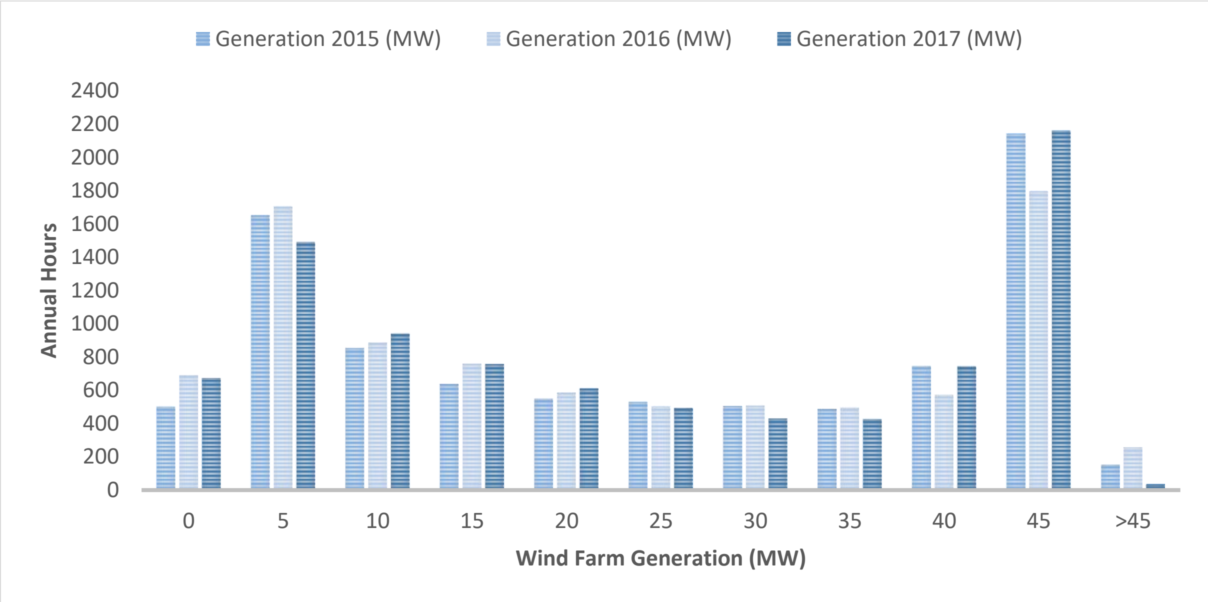

Figure 6. Histogram of Raggovidda Wind farm generation 2015-2017.

4.2.1.2 Smøla

Smøla wind farm is located in Smøla Municipality, in the Moere og Romsdal County. The wind farm is situated on flat and open terrain 10-40 metres above sea level. The wind farm was built in two phases. First, 20 wind turbines of 2 MW each were commissioned in September 2002, followed by 48 wind turbines of 2.3 MW each in September 2005 [15].

For the LCA analysis, it was assumed that the Smøla Wind-H_2 system consists of the 150 MW Smøla wind farm and the 2.5 MW PEM electrolyser (Figure 7).

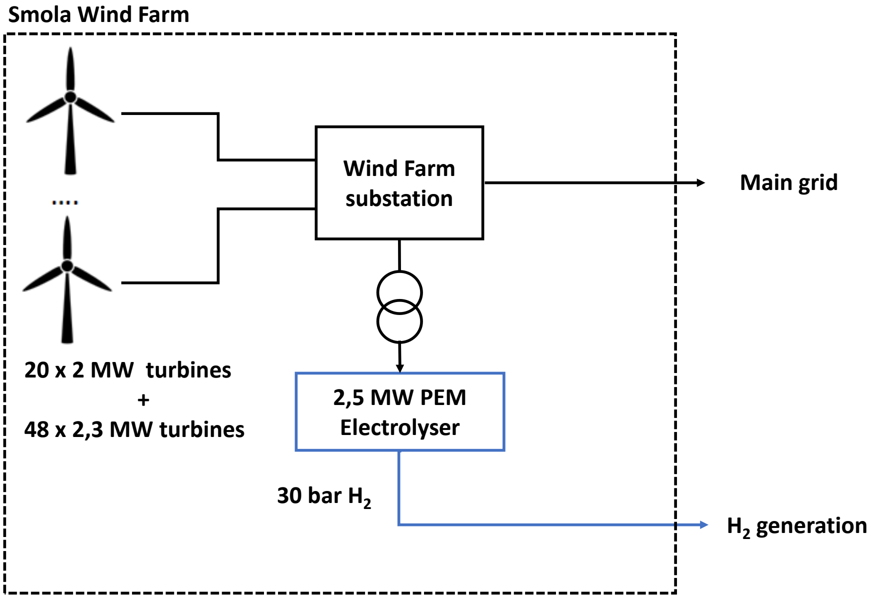

Figure 7. Conceptual layout of the Smøla Wind-H_2 system.

In addition, Table 10 summarises some general information, available in D5.3, regarding the Smøla wind farm [8].

Table 3. General information of the Smøla wind farm.

Smøla wind farm	
Parameter	**Value**
Nominal power	150 MW
Number of wind turbines	68
Turbine nominal power	2-2.3 MW
Connection point export power	45 MW
CAPEX	900 €/kW
OPEX	40 €/kW per year

Finally, Table 4 summarises the results of the statistical study of the real energy generation of the Smøla wind farm in 2015, 2016 and 2017. For each year, this table shows the maximum, minimum and mean power, as well as the total annual energy production and, as can be seen, there is a significant variation (≈30%) in the annual generation from year to year. On the other hand, regarding the hourly generation profile, Figure 9 shows a histogram with the results of the same three years.

Table 4. Summary of Smøla wind farm generation 2015-2017.

Smøla wind farm Generation 2015-2017				
Year	**Max (MW)**	**Min (MW)**	**Mean (MW)**	**Generation (MWh)**
2015	148.59	0	45.73	400638.76
2016	148.37	0	32.47	284497.28
2017	148.45	0	40.93	358574.74

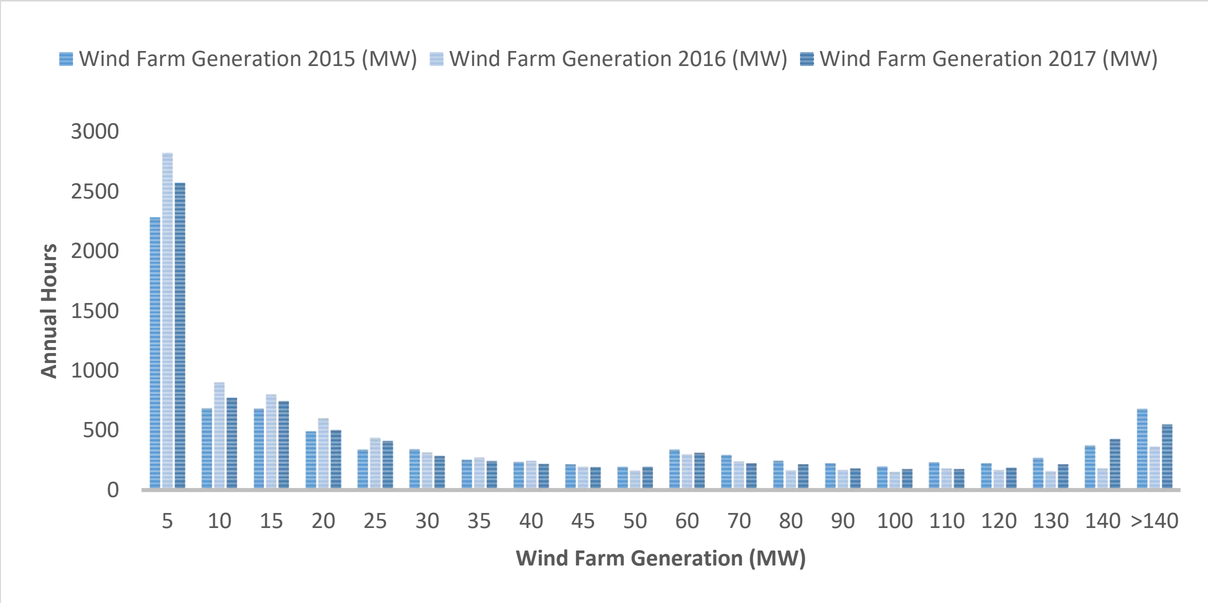

Figure 8. Histogram of Smøla wind farm generation 2015-2017.

4.2.1.3 Moncayuelo

The Moncayuelo wind farm is located in the municipality of Falces, in Navarre (Spain), and was installed in 2004. The wind farm consists of 32 turbines of 1.5 MW each, resulting in 48 MW of total installed power. Figure 9 shows the conceptual layout of the Moncayuelo Wind-H_2 system.

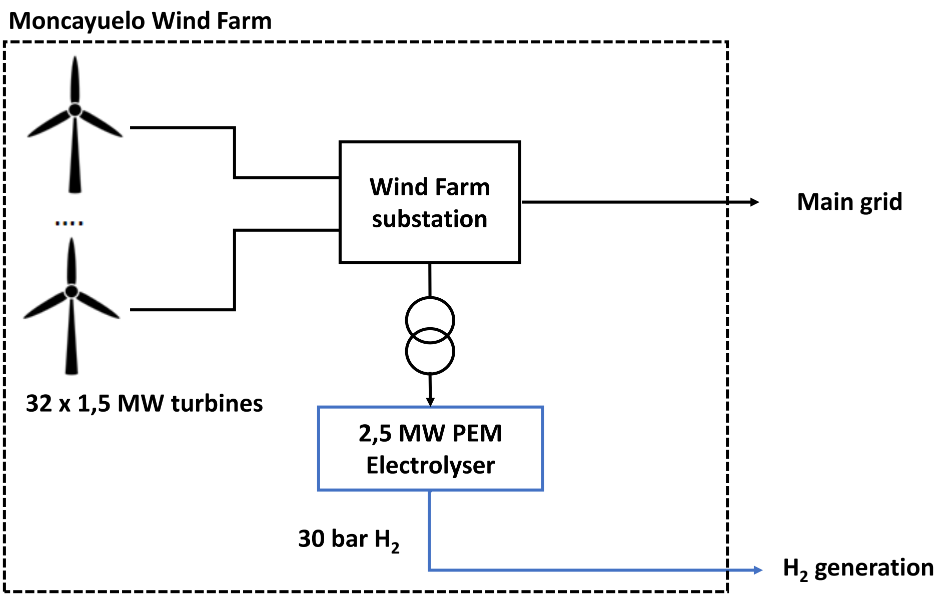

Figure 9. Conceptual layout of the Moncayuelo Wind-H_2 system.

With regard to technical data, Table 5 summarises some general data on the operation of the Moncayuelo wind farm.

Table 5. General information of the Moncayuelo wind farm.

Moncayuelo wind farm	
Parameter	**Value**
Nominal power	48 MW
Number of turbines	32
Turbine nominal power	1.5 MW
Connection point export power	48 MW
CAPEX	900 €/kW
OPEX	40 €/kW per year

Finally, Table 6 summarises the results of the statistical study of the real generation of the Moncayuelo wind farm for 2017. Maximum, minimum and mean power and the annual energy production are shown. Figure 10 shows the histogram of the wind farm generation.

Table 6. Summary of Moncayuelo wind farm generation 2017.

Moncayuelo wind farm Generation 2017				
Year	**Max (MW)**	**Min (MW)**	**Mean (MW)**	**Generation (MWh)**
2017	47.34x	0	16.60	145384

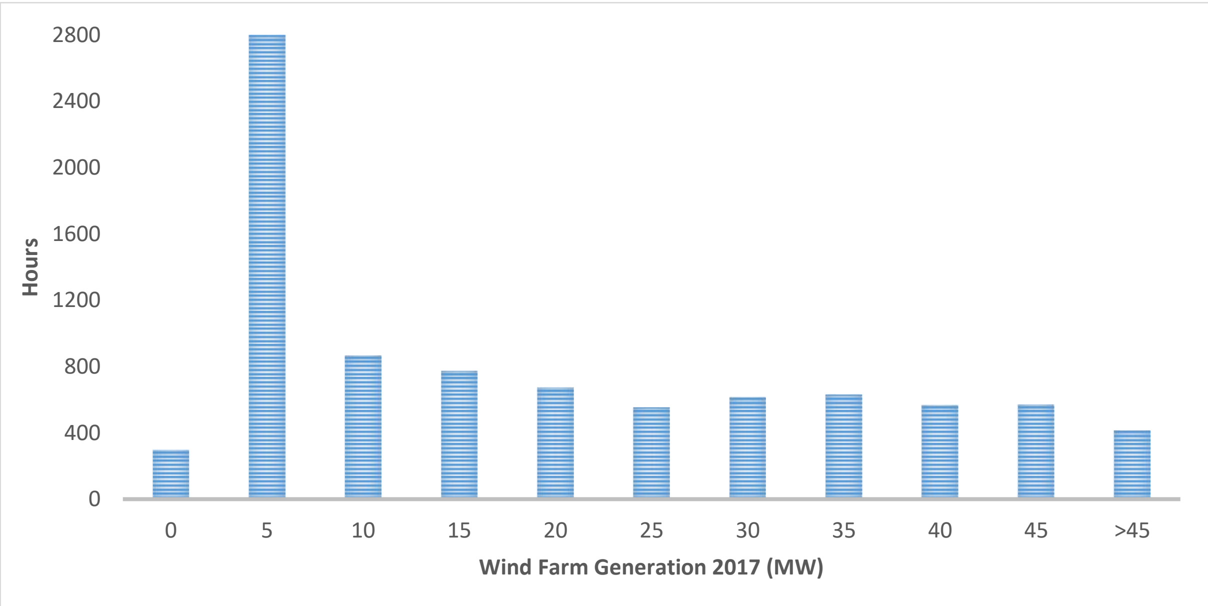

Figure 10. Histogram of Moncayuelo wind farm generation 2017.

4.2.2 Electrolyser

An electrolyser is an electrochemical device that converts electricity into H_2. The production of hydrogen through water electrolysis is a key part of the integrated system for converting wind energy into hydrogen. The type of electrolyzer installed in the pilot plant is Proton Exchange Membrane (PEM) of 2.5 MW, developed by CUMMINS.

The main characteristics of the electrolyser considered in the HAEOLUS project are summarized in Table 3. The rate of hydrogen production is 45 kg/hour (12000 Nm^3/day). The electrolyser has an estimated maximum lifetime of 20 years, but depending on usage, the lifetime may be shortened. Besides, the cycle-life is determined by two parameters: 40000 working hours and 5000 on/off switching cycles. The technical characteristics of the PEM electrolyser are summarized in Table 3.

Table 3. 2.5 MW Cummins hydrogenic electrolyser PEM data (from D5.3)

2.5 MW PEM Electrolyser	
Parameter	**Value**
Nominal Power	2.5 MW
Minimum Power	0.3 MW
Maximum Power	3.25 MW
Efficiency degradation at rated power and considering 8000 h operations / year	2%/year
Hydrogen delivery pressure	30 bar
Hydrogen production rate	45 kg/hour
Start-up time (cold start)	1200 seconds
Response time (warm start)	30 seconds
Shut down time (transition to standby)	1 seconds
Switch off time (include depressurization)	2 minutes
Ramp rate up/down	60 MW/min
Standby consumption	1 kW
Calendar life	20 years
Cycle-life	5000 on/off cycles
	40000 operation hours
CAPEX-electrolyser	1328 €/kW
OPEX per installed MW	60 €/MW year
Overhaul costs	354 €/kW

Inventory items for the maintenance of the electrolyser and the generation and consumption of de-ionized or demineralized water at a rate of 0.8 l/Nm^3 hydrogen produced were also included. Emissions during the operation of the electrolyser were waste heat (1.62 kWh/Nm^3 H_2), oxygen (0.5 kg/Nm^3 H_2) both released to atmosphere, and wastewater discharge (0.34 l/Nm^3 H_2).

4.2.3 Compression and storage tank

The storage element considered in the Raggovidda scenario is a 65 m^3 stainless steel storage tank. This tank can withstand hydrogen inlet flows at 300 bar from a 30/300 bar compressor connected to the hydrogen outlet of the electrolyser.

Hydrogen produced by the electrolyser is assumed to be compressed from the electrolyser output pressure of 30 bar to a pressure of 300 bar. A gas loss of 0.5% of the inlet volume is included, with the lost hydrogen included as emission to the atmosphere. The lifetime of the compressor is assumed to be 15 years. The technical characteristics of the compression and storage system are collected in Table 4.

Table 4. H_2 storage system data

Hydrogen plant data		
Parameter	**Value**	**Unit**
MP H_2 tank volume	64	m^3
MP H_2 tank pressure	30	bar
HP Compressor nominal power	200	kW
HP Compressor & other balance of plant elements power consumption average power	80-120	kW
MP & HP Calendar life	20	years
MP & HP Cycle life (if it makes sense for the compressor)	5000	cycles
	40000	working hours
HP CAPEX-tank (1.352 M€)	830	€/kg
HP CAPEX-compressor	350000	€
HP Compressor Life	15	years
OPEX per installed MW (HP compressor)	4	% (CAPEX)/year

4.2.4 Fuel cell

A fuel cell is an electrochemical system that transforms chemical energy of H_2 or other fuel into electricity (direct current). The fuel cell consumes H_2 and O_2 and produces electricity, heat and water.

As part of the HAEOLUS project, a 120 kW fuel cell, limited to 100 kW due to regulatory restrictions, has been installed to re-electrify the produced H_2 while the local H_2 market develops. The fuel cell used in this project was manufactured by CUMMINS as part of INGRID EU cofunded project [12] The technical characteristics of the considered fuel cell are collected in Table 5.

Table 5. 120 kW CUMMINS fuel cell data (from D5.3)

PEM Fuel Cell		
Parameter	**Value**	**Unit**
Nominal Power	0.12	MW
Minimum Power	0.012	MW
Maximum Power	0.132	MW
Efficiency derating due to usage or time	-	%/year
Hydrogen consumption rate (theoretically should be possible to obtain this number from power and efficiency)	9	kg/hour
Response time (warm start)	300	seconds
Shut down time	-	seconds
Ramp rate up/down	0.024	MW/min
Standby consumption	0.4	kW
Calendar life	10	years
Cycle-life	5000	cycles
	40000	working hours
CAPEX-Fuel cell	2250000	€/MW
OPEX per installed MW	45000	€/MW year
OPEX per produced MWh	-	€/MWh year

4.3 Description of Case Studies, input data and assumptions

Three different configurations have been considered for the HAEOLUS project system, depending on the use of the H_2 produced.

4.3.1.1 Hydrogen production as fuel

This use case basically consists of the production of hydrogen through electrolysis inside the wind farm, as a fuel for other uses outside the wind farm such as transport or industrial applications.

In this scenario, there is no fuel cell. Hydrogen is directly sold to external consumers, mainly to supply the hydrogen fuel demand of (road) vehicles. The simplest mode of operation for electrolysis would be to produce and store hydrogen continuously 24 hours a day to meet average fuel demand. However, this mode of operation does not correspond to the wind energy management mode, as it does not respond to the variable output of local or distant wind turbines, such as the hydrogen-based one in the HAEOLUS project. Furthermore, for the purpose of this study, it is assumed that existing fuel cell vehicles use the hydrogen generated and that there is a reasonable demand for H_2 as fuel in the market.

In this sense, the priority of this approach is to meet the hydrogen demand profile defined for a given period. For this purpose, the necessary energy from the wind farm will be used to feed the electrolyser that will produce the demanded hydrogen. The hydrogen obtained will be stored in a hydrogen tank. The filling level of the tank would be the main parameter representing the hydrogen demand profile to be covered.

Considering the above, this operation mode would be always active while the stored hydrogen level in the tank is under the reference hydrogen demand profile. It basically consists in producing hydrogen according to a specific hydrogen demand profile with the wind farm generation. Thus, the electrolyser would produce hydrogen using the required energy at each moment from that one generated in the wind farm. The hydrogen level dynamics is managed basically by the High Level Control (HLC) with a tracking lapse of time of 1 h. The main technical requirements to be fulfilled to achieve the energy storage operating strategy may provide a technical availability of the electrolyser of 95%. This means that the electrolyser could operate almost 23 hours per day producing hydrogen.

In this sense, LCA methodology is applied to evaluate the impacts caused per each kg of H_2 ready to be delivered. The LCI considered for this scenario to characterize the operation of the electrolyser is included in Table 7. On the other hand, the maintenance and replacements tasks of this equipment and production mode are summarized in Table 8.

Table 7. Main entering and exiting flows of the electrolyser operation (H_2 as fuel production)

Type of data	Name	Value	Units	Comments
General information	Maximum expected operation hours (per year)	8300	h/year	
	Technical availability	95	%	
	Reference flow of H_2	500	Nm^3/h	
Raw Materials	Water	600	l/h	Tap water purified by Reverse Osmosis (RO) system
Energy consumption	Electricity	2410	kWh	The system consumes 4.82 kWh/Nm^3

Products and co-products	H_2 (product)	500	Nm^3/h	
	O_2	250	Nm^3/h	
Waste flows	Waste heat	810	kWh/h	No heat recovery
	Wastewater	170	l/h	

Table 8. Maintenance of the electrolyser

Type of data	Name	Lifetime	Expected EoL treatment	Comments
Replacements	*Stack replacement**	*10 years*	*Refurbish*	
	High cycling valves	5 years	Recycling waste	2 valves required for the 10 years lifetime of the stack
	Membranes in RO system	5 years	Recycling waste	2 membranes required for the 10 years lifetime of the stack
	Small filters (RO system)	1 years	Recycling waste	10 filters required for the 10 years lifetime of the stack
	Safety valves	3 years	Recycling waste	3.33 valves required for the 10 years lifetime of the stack
Maintenance routine	Mixed bed resin replacement	2 years	l/day	5 resin bed needed for the 10 years lifetime of the stack. Mixed bed resin used: Tulsion MB106 and Amberlite MB20

**The impact of stacks manufacturing is not taken into account, as it should be accounted for the infrastructure category (upstream impacts). In this LCA, only impacts caused by operation and maintenance activities are considered. This includes consumables involved in maintenance operations, but not the manufacture of the main components, even if they are replaced.*

Considerations and assumptions for doing the LCA:

- It was assumed that the weight of each high cycling valve is 25 kg, and that the main construction material is cast iron. For the safety valves, it was assumed the same weight and that they are made of stainless steel.
- The membranes and filters of the reverse osmosis system were considered spirally wound modules, with an active surface of membrane of 32.5 m^2 per module. The environmental impacts of the manufacture of each module were estimated from the SimaPro data sheet "*seawater reverse osmosis module*".

On the other hand, the resources involved in the compression and storage stages are collected in Table 9. In this case, it was assumed that all H_2 generated in the electrolyser would be compressed and stored afterwards. To carry out the compression process, the electricity consumption of the compressor was estimated based on the results published by Agostini et al. 2018 [13]. In this paper, the authors estimated that the energy required for hydrogen compression to 70, 200, 350 and 700 bar is 2.6, 3.3, 3.7 and 4.1 kWh/kg H_2 respectively. On the other hand, no other resource consumptions have been identified in the H_2 compression and storage stages that need to be considered in an LCA with a gate-to-gate scope.

Table 9. Main entering and exiting flows of the H_2 storage system (including compression)

Type of data	Name	Value	Units	Comments
Input	Reference flow of H_2	1000	kg/day	
Energy consumption	Electricity	3.7	kWh/kg	Compression pressure: up to 350 bar

4.3.1.2 Energy storage to improve the integration of the wind farms with the utility grid

This use case involves the operation of an electrolyser, and in some cases also a fuel cell, to improve the integration of variable energy sources (such as a wind farm). This use case may include specific operating strategies such as price arbitrage or frequency regulation, among others.

The energy storage use case is related to the operation of the hydrogen system to improve the integration of wind farms into the grid. To this end, the electrolyser aims to produce H_2 at the lowest possible cost based on a given demand. To this end, the electrolyser will operate at variable power depending on the wind farm's integration requirements and signals from different energy markets.

To run these scenarios, three different operating strategies were identified in D5.3: congestion management, price arbitrage and frequency regulation.

➢ ***Congestion management***

This operation strategy basically consists in producing hydrogen when the wind farm generation exceeds the power limit at the connection point, due to either administrative or physical constraints. Thus, the electrolyser would produce hydrogen with the energy surplus generated in the wind farm, energy that, otherwise, would be wasted. In case the hydrogen system includes also a fuel cell, the hydrogen can be re-electrified whenever the wind farm power generation is below the export limit.

➢ ***Price arbitrage***

This exploitation strategy consists of storing energy in the form of hydrogen when the energy market price is low and then re-electrifying it when the energy market price is high. In case the system only includes an electrolyser, as analysed in the previous scenario, the aim of this operation strategy would be the production of hydrogen at the minimum possible cost.

Two different operation strategies might be implemented under this approach:

- *Fixed thresholds.* A fixed price threshold is defined and H_2 is produced only when the electricity cost drops below this limit. The selected value affects the number of yearly working hours of the electrolyser.
- *Variable threshold.* The threshold changes from day to day so that the minimum H_2 amount (120 t in 2.5 years) is produced by operating the electrolyser 4 hours per day. The minimum amount of produced H_2 is 120 t in 2.5 years, as required by EU in the FCH-02-4-2017 topic. This strategy could be consistent with a defined H_2 consumption rate and a limited capacity storage tank.

- ***Frequency regulation***

  Frequency regulation is related to active power regulation (up/down) for balancing the system frequency, which can vary due to the generation and consumption conditions of the energy resources connected to the grid.

In addition, in case of the energy-storage use case, the hydrogen system could have two possible configurations:

- Wind farm with the electrolyser operated under a demand response scheme. The hydrogen would be used for other purposes outside the wind farm. These are the main reference configurations and operating strategies that will be tested in the framework of the HAEOLUS project with the 2.5 MW PEM electrolyser.
- Wind farm with the electrolyser and the fuel cell. In this case, the hydrogen produced could also be used for re-electrification using the fuel cell. As the power of the fuel cell (100 kW) is much lower than that of the electrolyser (2.5 MW), operating strategies with this architecture will be evaluated in a limited way. Furthermore, hydrogen re-electrification is only economically justified for a few niche applications due to the low cycle efficiency of the hydrogen storage system.

To characterise the energy storage case study, the data needed to develop the LCI have been estimated by CUMMINS. Regarding the operation of the electrolyser, different scenarios have been considered assuming that the operating hours of the electrolyser change. In this analysis, we have not distinguished the reason why the electrolyser and the fuel cell do not work all the time and only work at certain times (congestion management, price arbitrage or frequency regulation). We assume that the environmental impacts depend more on the operating hours of the system and the amount of H_2 produced than on the economic and technical reasons for switching the equipment on and off. These studies are addressed in other project deliverables, such as D5.3 [8].

For this purpose, a sensitivity study has been carried out for this parameter (operating hours), considering between 4 h/day of operation up to 23 h of use per day. The consumption of the electrolyser and the compressor stage per hour of operation is shown in Table 10.

Table 10. Main entering and exiting flows of the electrolyser operation (H_2 as energy storage)

	Type of data	Name	Value	Units
Electrolyser	General information	Expected operation hours (per year)	4-23	h/day
		Reference flow of H_2	500	Nm^3/h
			178-1027	kg/day
	Raw Materials	Water	600	l/h
	Energy consumption	Electricity	2410	kWh
	Products and co-products	H_2 (product)	500	Nm^3/h
		O_2	250	Nm^3/h
	Waste flows	Waste heat	810	kWh/h
		Wastewater	170	l/h
Compression and storage	Energy consumption	Electricity	165.8	kWh/h

Besides, if H_2 is used for re-electrification, the impacts of the fuel cell need will also have to be determined. The only consumption associated with the fuel cell operation is the hydrogen flow (and oxygen to carry out the electrolytic conversion). On the other hand, the electricity production of the fuel cell has been estimated at 111.2 kWh, based on the approximations made by CUMMINS.

Table 11. Main entering and exiting flows of the fuel cell operation (H_2 as energy storage)

Type of data	Name	Value	Units
General information	Expected operation hours (per year)	4-23	h/day
Raw Materials consumption	H_2	111.2	Nm^3/h
	O_2	600	Nm^3/h
Energy generated	Electricity	100	kWh

4.3.1.3 Mini-grid

The term mini-grids refers to fully or partially islanded systems that include wind energy and typically other (decentralised) power generation. In this case, the use case for mini-grids is related to the operation of a hydrogen system to support isolated or weakly connected grids, e.g. on islands.

Two alternatives are considered with respect to the mini-grid connection to the main electricity grid [14]:

- **Weakly connected mini-grid,** with significant constraints with respect to their link to the main grid. In this case, the main purpose of hydrogen production is the storage of temporary surpluses of energy from renewables, the provision of a demand side management solution for energy supply (the electrolyser serving as a controllable / dispatchable load) and the contribution to the frequency and voltage stability of the grid.

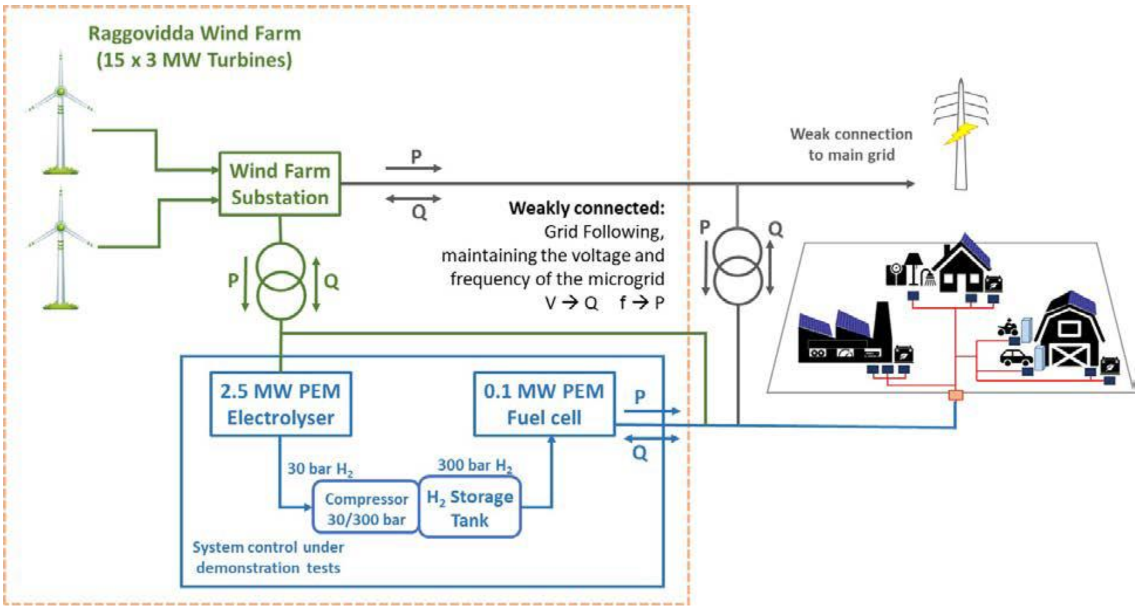

Figure 11. Conceptual layout of the wind-hydrogen system for the weakly connected mini-grid use case (from D8.2)

- **Fully islanded mini-grid** in which, without any connection to the main grid, the load is only fed by the wind-hydrogen system with the main constraints related to the provision of the required energy with proper quality and stability levels. Therefore, the main purpose is maintaining the power balance between generation and demand without the grid support.

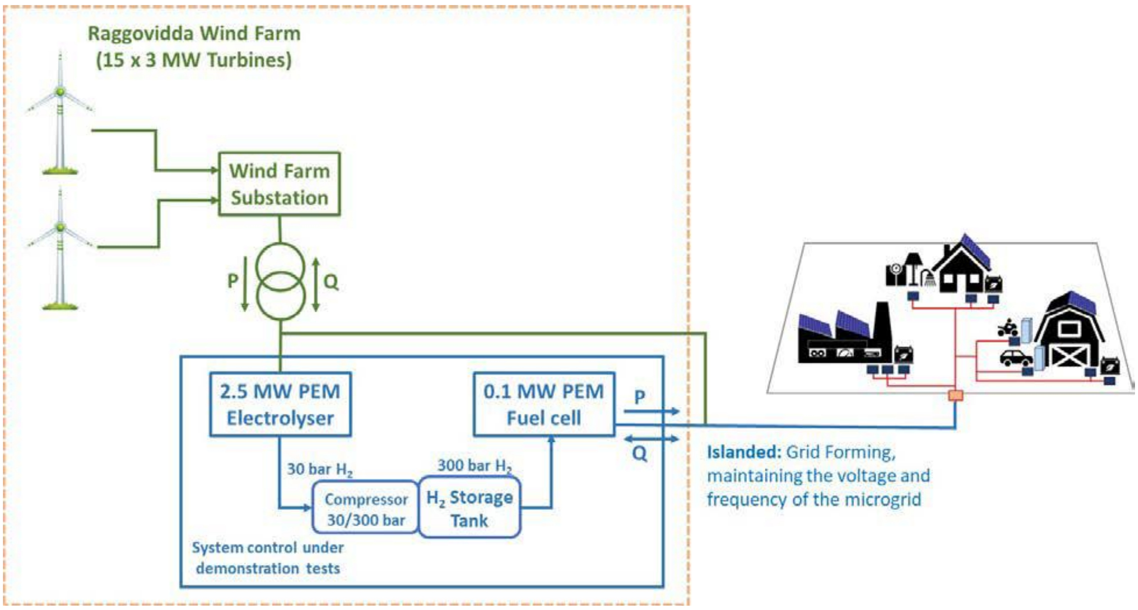

Figure 12. Conceptual layout of the wind-hydrogen system for the islanded mini-grid use case (from D8.2)

In stand-alone mode, the electrolyser and the fuel cell will operate to meet the load demand as needed. In weak connection mode, the additional participation in the electricity market will also be managed by covering the timescales of the daily and intraday markets.

In both cases, the studied system is formed by the wind farm, the electrolyser, the compression / storage stage and the fuel cell. The hours of operation of the electrolyser and the fuel cell will depend on the demand of the mini-grid, and this demand will vary from day to day and depending on factors such as season, day of the week, weather conditions, etc. To characterise this scenario, the inventory collected in Table 10 and Table 11 has been considered. In these tables, data is presented per hour of operation of each system, and therefore, values can be also extrapolated to this scenario.

5 Life Cycle Impact Assessment and interpretation of results

5.1 Raggovidda case study

Of the three wind farms described in the previous section, Raggovidda wind farm is the main demonstration location of HAEOLUS project, and therefore a deeper study of this case study has been performed in the current deliverable.

For this case study, the analysis of different operating modes has been considered. The first configuration of the HAEOLUS system is based on the production of H_2 as fuel. Once produced through the electrolytic process, the H_2 is compressed, stored and subsequently supplied for consumption off the wind farm site. Consequently, the functional unit considered in this analysis is one kg of H_2 ready for distribution. In this case, it is important to determine how many hours the electrolyser will run each day. These hours will depend on factors such as the availability of wind resource, the price of electricity, the capacity of the H_2 storage tank, etc. The reasons and strategies that can be implemented for deciding whether or not to produce H_2 at any given time are briefly summarized in section 4.3.

In this sense, we have analysed in this section how the impacts associated to each kg of H_2 would change depending on the number of hours of operation of the electrolyser. For this analysis, on the one hand, we have taken into account the resource consumptions derived from the operation of the electrolyser (energy consumption, water consumption, compressor energy consumption, etc.). These consumptions are proportional to the number of system operating hours. On the other hand, it has been considered that the maintenance and replacement of auxiliary equipment should be carried out at the periodicity indicated in Table 8. Although greater daily use of the electrolyser will anticipate wear of the components, for reasons of simplification of the study, it has been considered that maintenance is carried out annually and the components are replaced at the intervals shown in the table above, irrespective of the hours of use during that period.

In this light, the environmental impacts generated by the production of one kg H_2 in the electrolyser considered in the HAEOLUS project, taking into account that the electrolyser is operating 4 h per day and that the electricity consumed is produced in an onshore wind farm with 1-3 MW turbines, are shown in Table 12. Graphically, Figure 13 shows the distribution in percentages of the factors causing the impact measured by the different environmental indicators.

Table 12. Absolute environmental impacts of the production of 1 kg of H_2 (electrolyser production: 4 h/day)

Impact Categories	Units	Total	Purified water	Electricity	Wastewater	Maintenance (4 h/day)
Abiotic depletion	kg Sb eq	3.72E-05	9.23E-08	3.70E-05	1.72E-08	1.05E-07
Abiotic depletion	MJ	8.19E+00	7.23E-02	8.09E+00	8.10E-03	1.60E-02
Global warming (GWP100a)	kg CO_2 eq	6.74E-01	5.87E-03	6.57E-01	1.06E-03	9.41E-03
Ozone layer depletion (ODP)	kg CFC-11 eq	1.44E-06	3.29E-09	4.69E-08	3.92E-11	1.39E-06
Human toxicity	kg 1,4-DB eq	2.13E+00	5.83E-03	2.11E+00	2.47E-03	1.30E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.00E+00	4.50E-03	2.99E+00	1.38E-03	4.36E-03

Marine aquatic ecotoxicity	kg 1,4-DB eq	2.23E+03	8.92E+00	2.22E+03	1.70E+00	6.50E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	2.94E-03	1.69E-05	2.90E-03	3.19E-06	1.77E-05
Photochemical oxidation	kg C_2H_4 eq	1.94E-04	2.12E-06	1.91E-04	2.01E-07	7.23E-07
Acidification	kg SO_2 eq	2.94E-03	4.79E-05	2.88E-03	2.73E-06	6.53E-06
Eutrophication	kg PO_4^{-}-- eq	1.55E-03	9.50E-06	1.54E-03	1.18E-06	3.13E-06

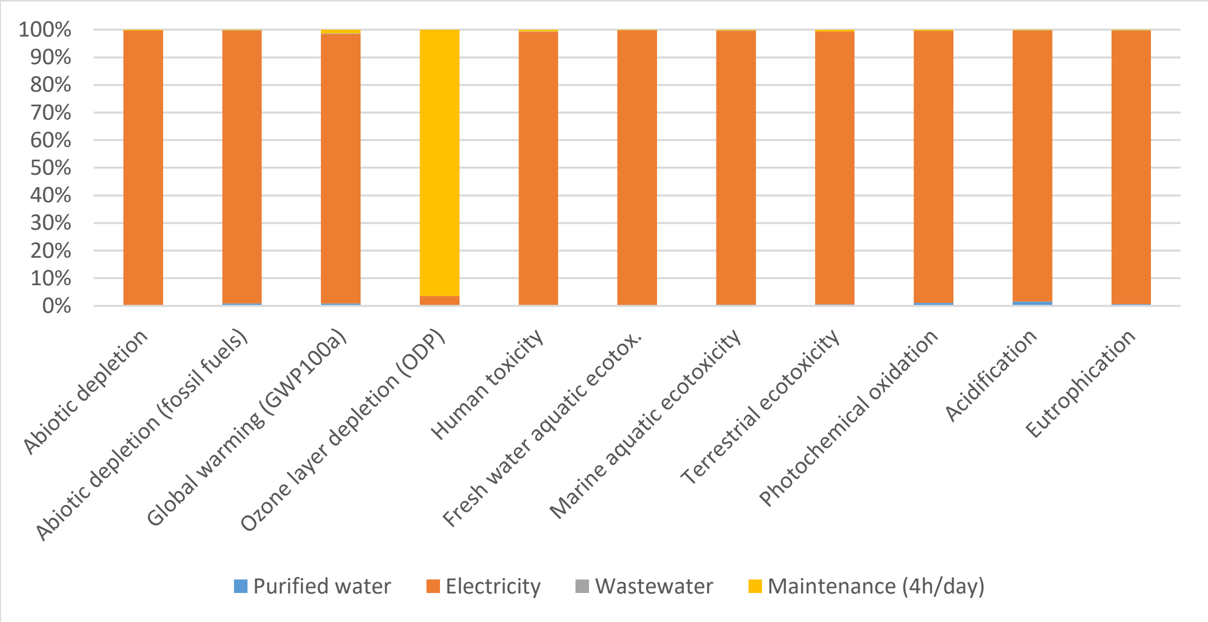

Figure 13. Relative environmental impact of the production of 1 kg of H_2 (electrolyser production: 4 h/day)

Looking at the results, it is clear from the above graph that the production of the electricity consumed by the electrolyser generates around 99% or even more of the total environmental impact attributable to each kg of H_2 produced. The only two exceptions are the global warming and the ozone layer depletion indicators, where electricity consumption generates 97.6% and 3.3% of the impact, and the rest of the impact is mainly due to maintenance and periodic replacement of auxiliary equipment (mainly valves and membranes). For the purpose of this LCA, we have considered electricity generation at a wind farm located in Norway, using the tab "*Electricity, high voltage {NO}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U*", which is available in the EcoInvent v3.7 database. The wind farm modelled in this datasheet consists of 1-3 MW wind turbines (Vestas V80 wind power plant modelled with a dataset for the wind turbine (moving + fixed parts) and a network connection each), and all their values were extrapolated from 2015 to the calculation year (2020). In this sense, the impacts of producing 1 kWh in a wind farm with the above characteristics, based on the EcoInvent models, are shown in Table 13. Among others, the production of each kWh generates 12.2 g of CO_2. If we analyse how this impact is generated (Figure 14), we can see that almost all of the GHG emissions from the energy generated in the wind farm come from the emissions caused in the manufacture of the wind turbines. And within these turbines, the use of cement for foundations, earthworks to prepare access roads and the use of materials such as glass fibre reinforced plastic and steel are the main generators of the impact.

Depending on the type of wind turbines used and the particularities of the wind farm, the results shown may vary. However, the use of the data available in the LCA databases makes it possible to work with an approximation of the possible results that one would expect to obtain in a wind farm of this type.

Table 13. Absolute environmental impacts of producing 1 kWh of electricity. Datasheet: Electricity, high voltage {NO}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U. *(EcoInvent)*

Impact Categories	Units	Total
Abiotic depletion	kg Sb eq	6.85E-07
Abiotic depletion (fossil fuels)	MJ	1.50E-01
Global warming (GWP100a)	kg CO_2 eq	1.22E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	8.69E-10
Human toxicity	kg 1,4-DB eq	3.90E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	5.54E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.10E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	5.37E-05
Photochemical oxidation	kg C_2H_4 eq	3.53E-06
Acidification	kg SO_2 eq	5.34E-05
Eutrophication	kg PO_4^{-}-- eq	2.85E-05

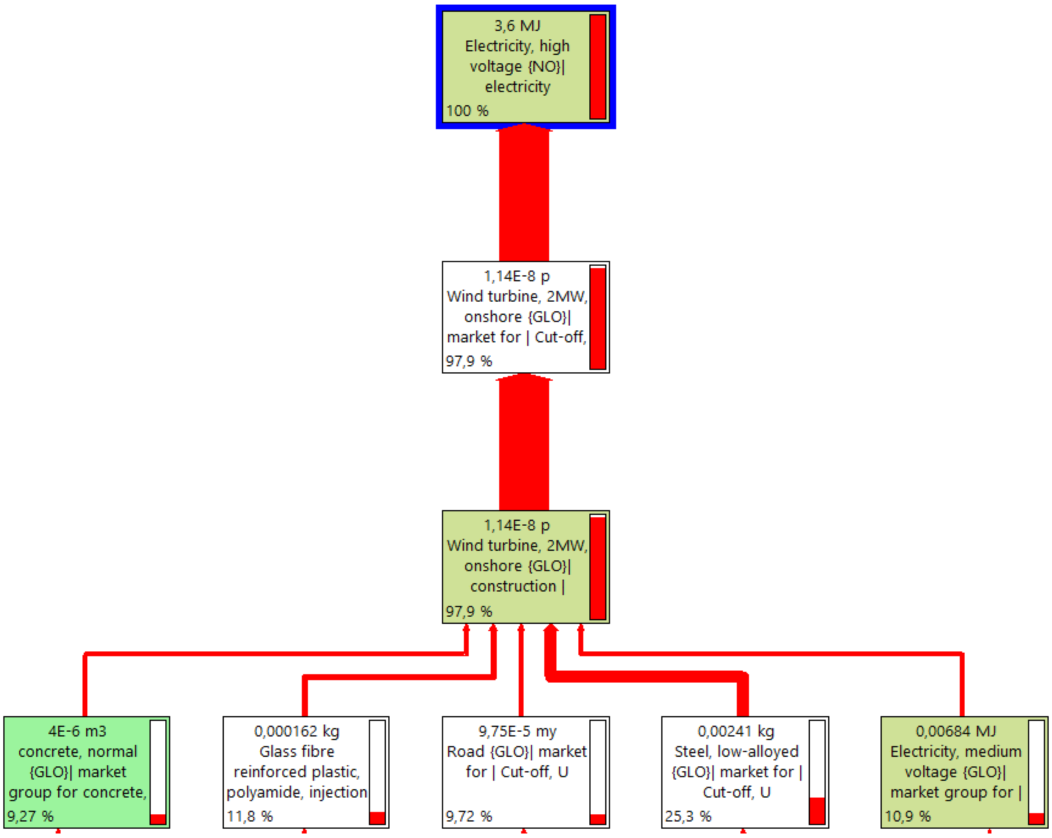

Figure 14. Network diagram of the Global Warming indicator. F.U.: 1 kWh electricity generated in a wind farm located at Norway. Wind turbines: 1-3 MW

In addition to the production of H_2 in the electrolyser, the use of a compression and storage system for the H_2 generated has been considered. Based on the description of this system available in the Life Cycle Inventory section, and more specifically on the data shown in Table 9, the only resource consumption to be taken into account in a gate-to-gate LCA analysis of these stages is the electricity consumption of the compressor. In this regard, it has been estimated that compressing each kg of H_2 up to a pressure of 350 bar consumes 3.7 kWh. In this sense, if we consider the impact of both producing H_2 in the electrolyser and compressing it, the impacts of each kg of H_2 stored in the tank are shown in Table 14.

Table 14. Absolute environmental impacts of producing 1 kg of H_2 (production, compression + storage).

Impact Categories	Units	Total	H_2 production	Electricity, compressor
Abiotic depletion	kg Sb eq	3.97E-05	3.72E-05	**2.53E-06**
Abiotic depletion (fossil fuels)	MJ	8.74E+00	8.19E+00	**5.54E-01**
Global warming (GWP100a)	kg CO_2 eq	7.19E-01	6.74E-01	**4.50E-02**
Ozone layer depletion (ODP)	kg CFC-11 eq	1.44E-06	1.44E-06	**3.21E-09**
Human toxicity	kg 1,4-DB eq	2.27E+00	2.13E+00	**1.44E-01**
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.21E+00	3.00E+00	**2.05E-01**
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.38E+03	2.23E+03	**1.52E+02**
Terrestrial ecotoxicity	kg 1,4-DB eq	3.14E-03	2.94E-03	**1.99E-04**
Photochemical oxidation	kg C_2H_4 eq	2.07E-04	1.94E-04	**1.31E-05**
Acidification	kg SO_2 eq	3.14E-03	2.94E-03	**1.98E-04**
Eutrophication	kg PO_4^{-}-- eq	1.66E-03	1.55E-03	**1.05E-04**

In this case, most of the impact of the stored H_2 is due to the electrolysis process. The electricity consumption of the compressor is responsible for less than 6% of the total impact measured with any of the indicators of the CML evaluation method.

On the other hand, so far it has been assumed that the electrolyser only runs 4 hours per day. This value has been chosen because, as indicated in D5.3, it is the minimum number of hours per day that the electrolyser should operate in order to meet the minimum target initially set for the HAEOLUS project (produce 120 t of H_2 in 2.5 years) [8]. However, in a more ambitious scenario, the number of operating hours could be substantially increased, to the point where the electrolyser could operate for 23 hours per day. In this case, the impacts attributable to each kg of H_2 from the maintenance activities would be lower and therefore, the environmental performance of the fuel generated would be optimised. For this scenario, the environmental impacts of each kg of H_2 already stored under pressure are shown in Table 15 and graphically, in Figure 15.

Table 15. Absolute environmental impacts of the production of 1 kg of H_2 (electrolyser production: 23 h/day)

Impact Categories	Units	Total	Purified water	Electricity (electrolyser)	Wastewater	Maintenance (23 h/day)	Electricity (compressor)
Abiotic depletion	kg Sb eq	3.96E-05	9.23E-08	3.70E-05	1.72E-08	1.83E-08	2.53E-06
Abiotic depletion (fossil fuels)	MJ	8.73E+00	7.23E-02	8.09E+00	8.10E-03	2.78E-03	5.54E-01
Global warming (GWP100a)	kg CO_2 eq	7.11E-01	5.87E-03	6.57E-01	1.06E-03	1.64E-03	4.50E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	2.95E-07	3.29E-09	4.69E-08	3.92E-11	2.41E-07	3.21E-09
Human toxicity	kg 1,4-DB eq	2.26E+00	5.83E-03	2.11E+00	2.47E-03	2.26E-03	1.44E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.21E+00	4.50E-03	2.99E+00	1.38E-03	7.58E-04	2.05E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.38E+03	8.92E+00	2.22E+03	1.70E+00	1.13E+00	1.52E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	3.12E-03	1.69E-05	2.90E-03	3.19E-06	3.08E-06	1.99E-04
Photochemical oxidation	kg C_2H_4 eq	2.06E-04	2.12E-06	1.91E-04	2.01E-07	1.26E-07	1.31E-05
Acidification	kg SO_2 eq	3.13E-03	4.79E-05	2.88E-03	2.73E-06	1.14E-06	1.98E-04
Eutrophication	kg PO_4^{-}-- eq	1.65E-03	9.50E-06	1.54E-03	1.18E-06	5.45E-07	1.05E-04

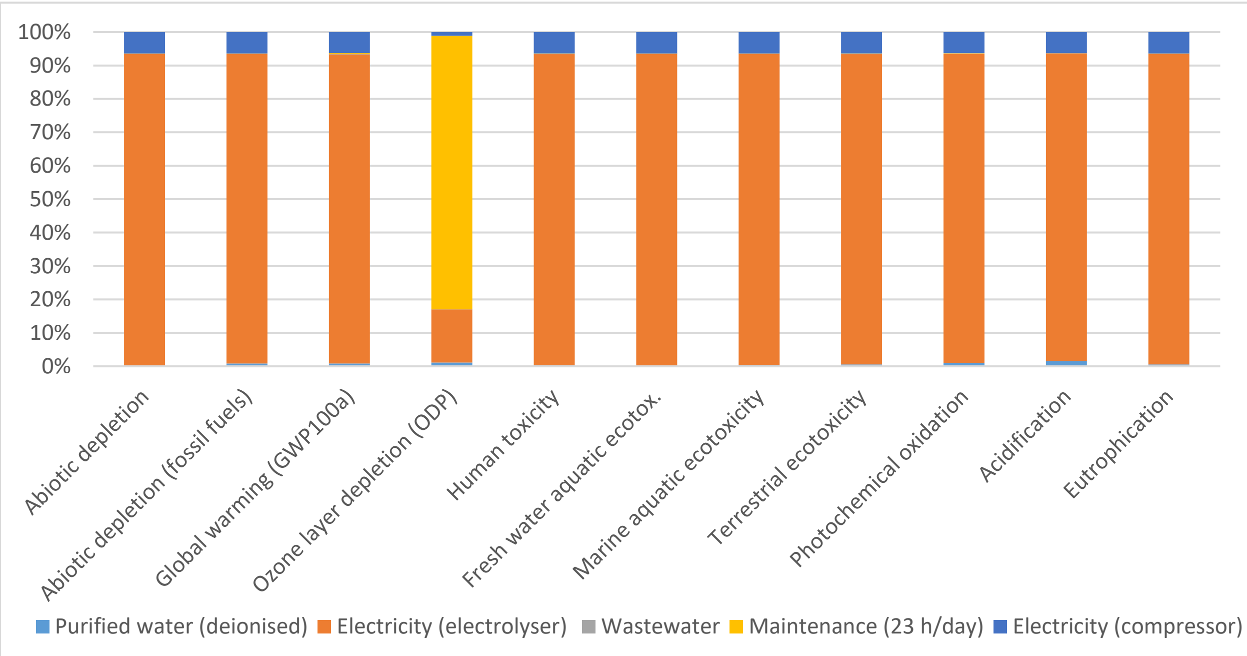

Figure 15. Relative environmental impact of the production of 1 kg of H_2 (electrolyser production: 23 h/day)

In this case, all impacts have been reduced to a greater or lesser extent compared to the results obtained in Table 14. However, in most cases, the percentage reduction is small. For example, in this new scenario (23h/day of operation), the production and storage of one kg of H_2 generates 2.97E-07 kg CFC11eq, compared to the 1.44E-06 kg CFC11eq that had been obtained with 4 hours of electrolyser operation. This is one of the indicators where the greatest variation has been recorded, since, as can be seen in the figure, maintenance activities have a significant weight in the total impact of the ozone layer depletion indicator. Regarding the global warming indicator, a GHG emission reduction from 0.719 kg CO_2eq to the 0.711 kg CO_2eq has been recorded. In addition, it should be taken into account that it has been considered that the replacement of the auxiliary electrolyser components will be carried out every certain predetermined time, without taking into account the number of hours that the equipment has been in operation, which is not entirely true.

As a final analysis of this part, Figure 16 shows how the global warming indicator would vary if the number of hours of operation of the electrolyser per day changes. The limits of the curve are the scenarios that have been analysed in more detail and correspond to the maximum (23 h/day) and minimum (4 h/day) number of hours. As a consequence and based on the average number of hours the electrolyser is expected to operate, we can estimate the emissions associated with the H_2 generated using this curve.

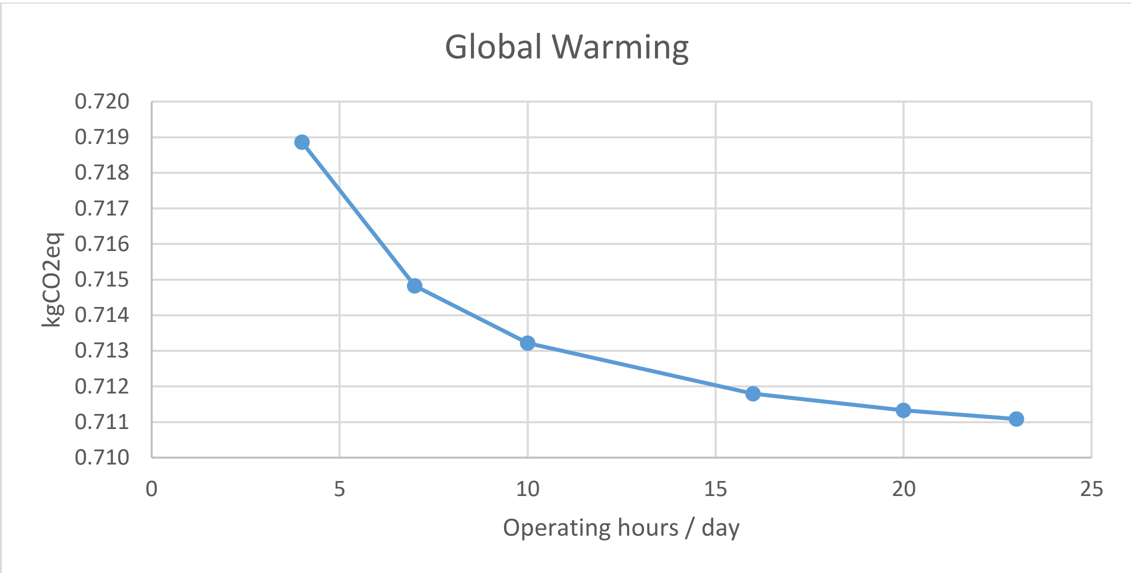

Figure 16. GHG emissions from H_2 generated as a function of the number of hours of operation of the electrolyser

Among the possible applications of the generated H_2, its use as a fuel for road vehicles is one of the most promising applications and one of the possible axes for moving the economy towards its decarbonisation. Hydrogen does not involve direct emissions in its use, which makes it a promising clean fuel for transport [15].

In order to compare the environmental impacts of using green H_2 as a fuel in road vehicles with the environmental impacts of H_2 production processes from fossil fuels, a brief literature review has been carried out to get an overview of the magnitude of environmental improvement that could be achieved in the future with further development of green hydrogen production processes.

According to the International Energy Agency, 96.5% of the hydrogen produced today is grey hydrogen from the natural gas reforming process, while only 3.5% comes from water electrolysis processes [16]. Therefore, it is important to know the impacts associated with the main H_2 production routes in order to define the benchmarking scenario with which to compare the results of the green H_2 produced in the HAEOLUS project.

To this end, we have carried out a literature review to study the LCAs performed by other authors on different H_2 production processes and compare with each other. In this regard, we have found numerous studies in the literature that analyse the emissions generated in natural gas reforming processes (SMR process), which is the most extent production route. In these studies, it has been found that the GHG footprint of each kg of generated fossil H_2 is around 11.5 $kgCO_2$ /kgH_2 [17], [18]. This result, which seems to be widely accepted by the scientific community as an average value, differs from the value available in the EcoInvent database, which is also a source widely used by LCA teams. Among others, some authors such as Chen and Lam [19], estimated in their paper the impacts attributable to grey hydrogen from the process named "*Hydrogen, gaseous (GLO) market for*" in the EcoInvent 3.6 database, to which they add the impact of the electricity needed to compress the H_2 and the impacts of transport. The result obtained is that the production of each kg of H_2 generates around 2 kg CO_2 eq, which, for other authors, such as de Kleijne et al. [18], is an erroneous result. In fact, these authors states in their paper that "*The use of this EcoInvent value in LCA studies has led to incorrectly low GHG footprints*".

For this reason, we have decided not to use the EcoInvent database to characterise the impacts caused by the hydrogen production process from fossil sources and have taken the value of 11.5 $kgCO_2$ /kgH_2 as a reference value.

Regarding the emissions involved in the processes of green H_2 production, it has been found in the literature that the environmental footprint of H_2 can change considerably from one study to another depending on the origin of the electricity used to carry out the electrolysis. Among the many existing studies, the one published by de Kleijne et al. [18] has been selected because it has been published recently and allows an accurate comparison with the results obtained so far in this deliverable. As part of its publication, Figure 17 shows the GHG footprint of green hydrogen produced with different renewables (wind or solar) and current (2020) and future (2030) average grid electricity, based on the life-cycle inventory published in [20]. Besides, different approaches are considered depending on how the oxygen produced is treated. Typically, oxygen that is co-produced in water electrolysis is vented to air and all the process emissions are attributed to the produced H_2. However, the oxygen could also be purified for use in a downstream process. On the one hand, when using a "system scale-up by substitution" approach, it is assumed that the co-produced oxygen replaces conventional oxygen production by air separation elsewhere. On the other hand, the economic approach allocates the process emissions according to the economic value of the hydrogen and oxygen produced.

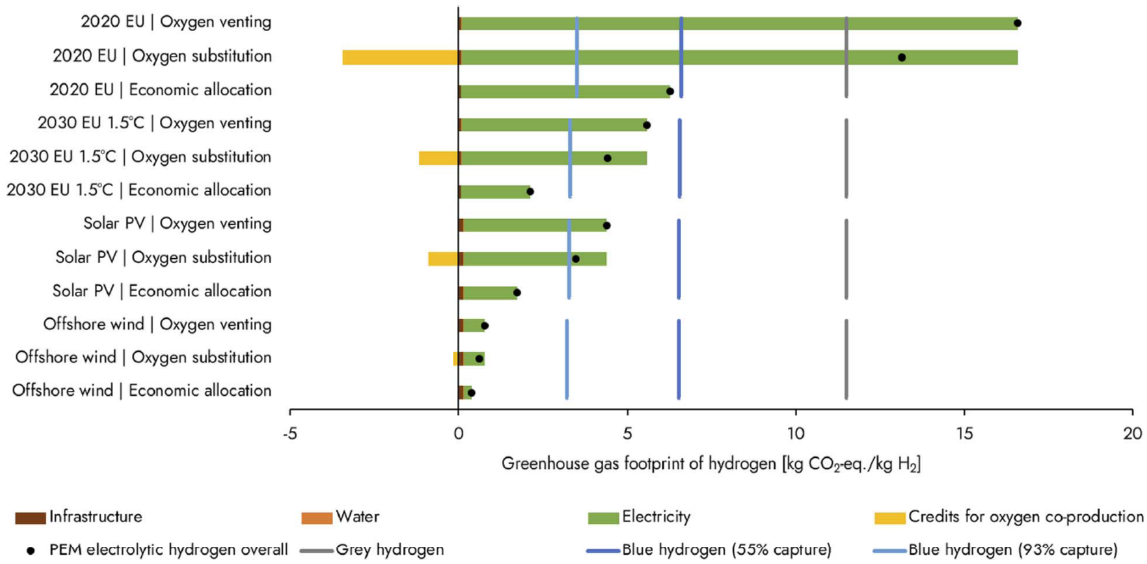

Figure 17. The greenhouse gas footprint of PEM electrolytic hydrogen for different electricity sources and multi-functionality approaches in kg CO_2-eq per kg H_2

From this study, it was obtained that hydrogen powered by wind energy presents a GHG footprint of 0.4-0.8 kg CO_2eq/kg H_2. These values are in line with those obtained in the project (0.71 kg CO_2eq/kg H_2). Besides, it is worth mentioning that the wind farm considered by Kleijne et al. [18] had larger turbines, and this tends to reduce the impact of each kWh generated (5 MW). On the other hand, using solar PV for hydrogen production generates 1.7-4.4 kgCO_2eq/ kg H_2, which is approximately five times larger compared to wind-based hydrogen. Finally, using the 2020 EU grid mix, electrolytic hydrogen has a GHG footprint of 6.3–16.6 kgCO_2-eq / kg H_2, which is in most cases higher than grey hydrogen. Finally, it is expected that in the future a cleaner 2030 grid mix (compatible with the EU targets for limiting warming to 1.5 ºC) results in a lower, but still sizable GHG footprint (2.1–5.6 kgCO_2eq / kg H_2) [18].

As a conclusion of this brief literature review, it has been found that, on the one hand, the results obtained in the analysis of H_2 produced with the HAEOLUS project data are in agreement with the results obtained by other authors for equivalent systems. On the other hand, it has been shown that the origin of the electricity used in the electrolysis process can significantly influence the results obtained. Furthermore, most authors agree that electrolysis powered by electricity from wind farms is one of the most promising options and that it may generate the greatest environmental benefit in the future decarbonisation of the transport sector.

In addition to selling H_2 for use as fuel outside the boundaries of the wind farm, the HAEOLUS project has tested the use of a fuel cell for the reelectrification of H_2. This strategy allows H_2 to be used as an energy storage system to improve the integration of wind farms into the grid, as well as to supply energy in mini-grids. A more detailed explanation of the implications of these scenarios and the different strategies that can be applied within each of them is detailed in sections 4.3.1.2 and 4.3.1.3.

Taking into account that the fuel cell used in the project has been estimated to generate up to 100 kWh of electricity and its consumption of H_2 per hour is 111.2 Nm^3 (9.92 kg H_2), the environmental impacts attributable to each kWh generated are shown in Table 16.

Table 16. Absolute environmental impact of producing 1 kWh of electricity from H_2 in a fuel cell (reelectrification)

Impact Categories	Units	Total
Abiotic depletion	kg Sb eq	3.94E-06
Abiotic depletion (fossil fuels)	MJ	8.69E-01
Global warming (GWP100a)	kg CO_2 eq	7.16E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	1.43E-07
Human toxicity	kg 1,4-DB eq	2.26E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.19E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.37E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	3.12E-04
Photochemical oxidation	kg C_2H_4 eq	2.06E-05
Acidification	kg SO_2 eq	3.12E-04
Eutrophication	kg PO_4^{-}-- eq	1.65E-04

In this assessment, we are considering that the impacts per kg of H_2 produced are constant. However, the actual impact could vary depending on the stop/start cycles of the electrolyser and the fuel cell. Furthermore, in this case we are not considering the impact associated with the transport of pressurised H_2 when it is consumed outside the wind farm (as in the case of mini-grids).

To analyse the impact associated with the transport of H_2, TECNALIA has considered (as an example) a scenario in which H_2 is transported from the wind farm where it is generated to the location of a fuel cell 400 km away. The transport is carried out by road with a EURO 6 freight lorry and a pressurised hydrogen storage tank type II, with a capacity of 80 kg and mainly made of steel.

For example, if we want to know the impacts of one kg of pressurised H_2 not only in the wind farm but also after 400 km of transport, we should add the impacts calculated in Table 14 and Table 17. In this case, and among others, the total global warming impact of one kg of H_2 would be 0.849 kg CO_2eq, of which 0.719 kg CO_2eq (85%) would come from electrolysis process and 0.130 kg CO_2eq (15%) from transport (Figure 18). Furthermore, taking into account that the fuel cell consumes 9.92 kg of H_2 for each 100 kWh of electricity produced, the GHG emissions associated with each kWh produced (considering transport) will be 8.45E-02 kg CO_2eq.

Table 17. Absolute impacts associated with the transport of 1 kg of H_2 (400 km)

Impact Categories	Units	Transport total impact	H_2 transport	Storage tank manufacturing
Abiotic depletion	kg Sb eq	8.62E-07	4.10E-07	4.52E-07
Abiotic depletion	MJ	1.82E+00	1.26E+00	5.61E-01
Global warming (GWP100a)	kg CO_2 eq	1.30E-01	8.53E-02	4.51E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	1.77E-08	1.51E-08	2.58E-09
Human toxicity	kg 1,4-DB eq	5.77E-02	3.16E-02	2.61E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	4.81E-02	1.56E-02	3.25E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	8.67E+01	2.91E+01	5.76E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	2.42E-04	1.06E-04	1.36E-04
Photochemical oxidation	kg C_2H_4 eq	1.60E-05	9.86E-06	6.12E-06

Acidification	kg SO_2 eq	3.06E-04	1.95E-04	1.11E-04
Eutrophication	kg PO_4^{-}-- eq	1.67E-04	4.49E-05	1.22E-04

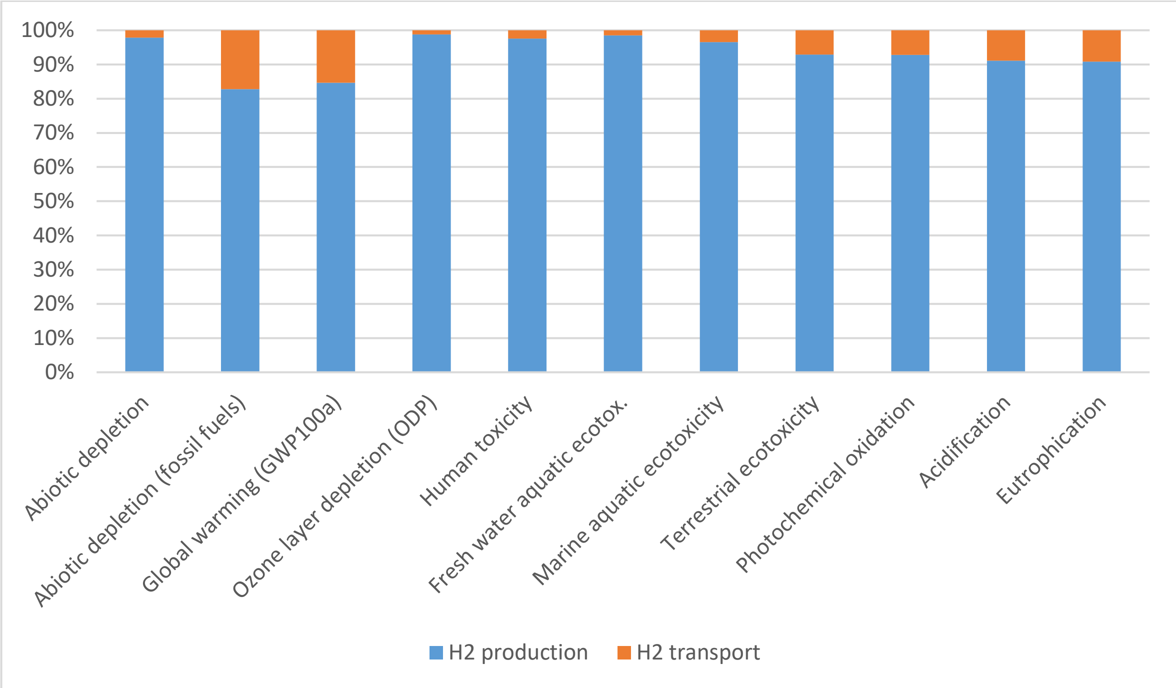

Figure 18. Relative environmental impact of the production of 1 kg of H_2 considering transport

Finally, to better understand the significance of the results obtained per kWh generated in the H_2 reelectrification, an analysis of the Norwegian electricity generation system in the year 2021 has been carried out to compare the results of the HAEOLUS system electricity with the average value of electricity in the country.

In this sense, Norway is a country where traditionally almost all electricity has been generated from hydropower. In fact, in 2012, more than 96% of the energy generated was hydroelectric. However, in recent years, wind power has significantly increased its share in the energy mix, accounting for 7.5% of the total in 2021 [21]. The electricity mix of Norway in 2021 is depicted in Figure 19.

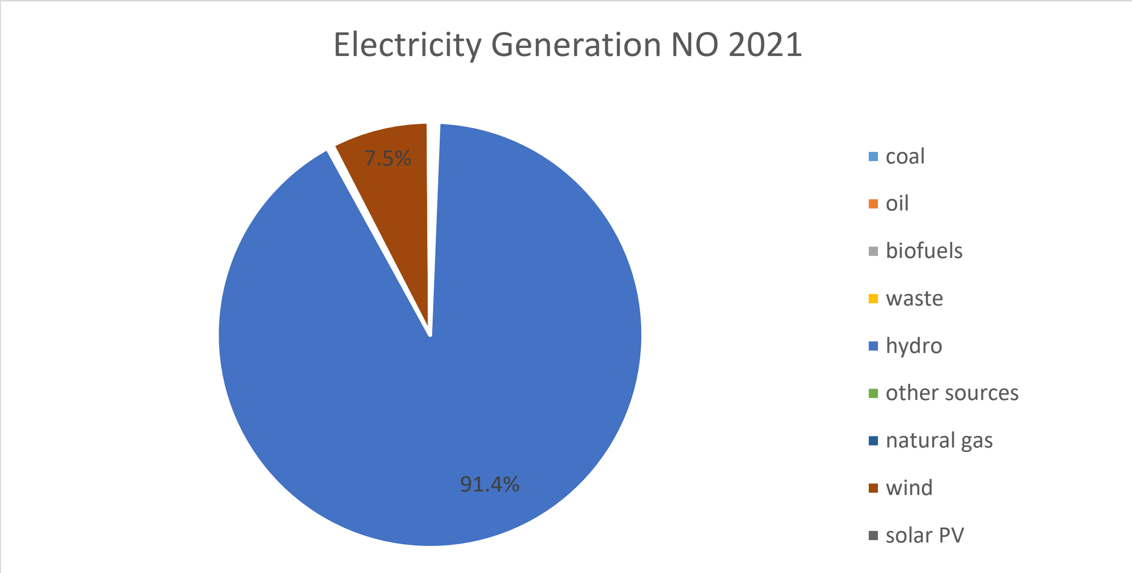

Figure 19. Electricity generation by source in Norway, 2021 [21]

Based on the information available in the figure above, the environmental impacts associated with the production of one kWh using the Norwegian electricity mix have been modelled with Simapro and the EcoInvent database. The results obtained are shown in Table 18.

Table 18. Impact of one kWh generated with the Norwegian electricity mix, 2021.

Impact Categories	Units	Norwegian electricity mix, 2021
Abiotic depletion	kg Sb eq	6.63E-07
Abiotic depletion	MJ	1.18E-01
Global warming (GWP100a)	kg CO_2 eq	1.96E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	5.91E-10
Human toxicity	kg 1,4-DB eq	3.07E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	4.36E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	3.53E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	6.97E-04
Photochemical oxidation	kg C_2H_4 eq	2.39E-06
Acidification	kg SO_2 eq	4.77E-05
Eutrophication	kg PO_4^{-}-- eq	3.01E-05

Among other impacts, the production of one kWh of electricity in Norway generates 19.6 g CO_2eq (global warming indicator). This value is much lower than the average emissions generated by the European electricity mix, which have been estimated at 406 g CO_2eq / kWh according to the information available in the EcoInvent database. The astonishingly low emission factor of the electricity produced in Norway makes it one of the cleanest and most environmentally friendly countries in terms of energy production sources, mainly based on renewable sources (hydro and, to a lesser extent, wind).

If we compare the impact of Norwegian electricity mix with the impact caused by H_2 fuel cell electricity (case study of the HAEOLUS project), we can see that, although the impact of the electricity from the fuel cell is very low compared to other sources of electricity production, the impact of each kWh generated is significantly higher than the impact of the electricity produced from the Norwegian energy mix (19.6 g CO_2eq vs 71.6 -84.5 g CO_2eq).

Therefore, from an environmental point of view, consuming electricity from the Norwegian grid has less impact than the electricity produced with the fuel cell. Furthermore, in view of the conclusions drawn from the techno-economic analysis carried out in D5.3, the integrated wind-H_2-FC system is also not economically viable to produce H_2 for reelectrification at Raggovidda as the obtained H_2 production costs, in the range of 11 to 13 k€/t, are not competitive according to the current status of those of around 6 k€/t [8]. However, the wind-H_2-FC system may be an excellent alternative for remote areas not connected by the main grid or other isolated areas.

5.2 Smøla

In addition to the analysis carried out at the main demonstration site of the project, which is the Raggovidda wind farm, the first of the replication scenarios selected to reproduce the project results and to estimate theoretically how the project system would be implemented in other sites is the Smøla wind farm. At this location, the project considers the installation of a wind + H_2 system, but not a fuel cell.

Regarding the analyses carried out for this location, D5.3 contains an economic and social assessment of the impacts generated at this site under two different operating strategies: “optimal H_2 production” and “congestion management”. As a result, this deliverable establishes that, in both cases, the smaller electrolysers were found to be the most cost-effective and that the operation for the "optimal H_2 production" is cost competitive and the costs obtained for the "congestion management" scenario are not [8].

As regards the environmental impact assessment, the Smøla wind farm has higher installed power than the Raggovidda wind farm (150 MW compared to 45 MW). However, Smøla's turbines have less nominal power than Raggovidda’s (2.2-2.0 MW compared to 3.0 MW in Raggovidda), and the number of installed turbines is higher in Smøla (Smøla: 68, Raggovidda: 15). A summary of the characteristics of both wind farms can be found in Table 1 and Table 3.

In this sense and having analysed the characteristics of the Smøla wind farm, we consider that it would be correct to estimate the impact associated with each kWh of electricity generated in this wind farm from the same datasheet of the EcoInvent 3.7 database file that was used for the Raggovidda wind farm “*Electricity, high voltage {NO}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U*”. This datasheet considers the average impact of the construction of a wind power plant consisting of 1-3 MW wind turbines, and it also considers the operation of the wind power plant and the necessary maintenance tasks. Besides, the datasheet was modelled for Norway, so their use is a fairly reliable approximation of the impacts generated by a wind farm of this type. As a result, it was obtained that the production of each kWh generates, among others, 12.2 g CO_2eg. The rest of the environmental impacts associated with each generated kWh are collected in Table 13.

As for the use of electricity from the wind farm to produce H_2 in the assumed installed electrolyser, the operation of this equipment will depend on factors such as the price of electricity at any given time, the level of grid congestion, the capacity of the H_2 storage tank, the demand for H_2, etc. However, as the study of these factors is not within the scope of this report. In this case, the study has focused on analysing what the environmental impacts of each kg of H_2 produced would be if the electrolyser were in operation from 4 to 23 hours a day. On the one hand, Table 14 shows the results obtained with 4 hours of H_2 production per day, and Table 15, for 23 hours per day. On the other hand, Figure 16 shows how the global warming indicator would vary depending on the hours of operation of the electrolyser. In all cases, it has been estimated that around 0.71 kg of CO_2eq are generated per kg of H_2 produced.

As a possible extension to the details of this LCA, it would be necessary to analyse the particularities of the Smøla wind farm on the basis of actual data from the wind farm operation, but it is not expected that there would be major differences from the results estimated in the LCA of this report.

5.3 Moncayuelo

The second scenario chosen for the replication of the project results is the Moncayuelo wind farm. In this case, the Moncayuelo area is located in the Spanish region of Navarra and, as in the case of Smøla, the HAEOLUS project considers the theoretical installation of a wind + H_2 system, but not a fuel cell.

The Moncayuelo wind farm consists of 32 turbines of 1.5 MW, resulting in 48 MW of total installed power. This means that the total installed capacity is very similar to that of the Raggovidda wind farm (45 MW). However, as its turbines have less nominal power (1.5 MW compared to 3.0 MW), the Spanish wind farm has more than twice as many turbines as the Norwegian one (32 versus 15). A summary of the characteristics of Moncayuelo wind farm can be found in Table 5.

As for the analyses carried out for this location in D5.3, the performances of the electrolysers were studied considering their operation in two scenarios: "Optimal H_2 production" and "Secondary frequency regulation". As a result, this deliverable established, on the one hand, that the smaller electrolysers were the most cost-effective and, on the other hand, that the higher the number of electrolyser working hours, the lower the cost of H_2 produced and therefore, the better the results [8].

For this scenario, the environmental impacts attributable to each kWh generated at the wind farm have been estimated from the datasheet "*Electricity, high voltage {ES}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U*", available in the EcoInvent v3.7 database. As in the case of the datasheet used to model the Norwegian wind farms, the wind farm modelled in the Spanish datasheet consists of 1-3 MW wind turbines (Vestas V80 wind power plant modelled with a dataset for the wind turbine (moving + fixed parts) and a network connection each), and all their values were extrapolated from 2015 to the calculation year (2020).

In this sense, the impacts of producing 1 kWh in a wind farm with the above characteristics and located in Spain, based on the EcoInvent models, are shown in Table 19. Among others, the production of each kWh generates 12.4 g of CO_2eq. It should be recalled at this point that the emissions generated per kWh in a Norwegian wind farm of the same characteristics were estimated at 12.2 g CO_2eq, which means that EcoInvent considers that an equivalent wind farm generates almost 2% more emissions if it is located in Spain rather than in Norway. This variation is mainly due to EcoInvent's internal data, where the average size of Spanish and Norwegian wind farms and the type of turbines frequently installed are considered. For our case study, given that the Raggovidda wind farm has more powerful turbines than the Moncayuelo wind farm, the expected result would be that emissions per kWh generated would be lower in Raggovidda, which is in line with EcoInvent estimations.

Table 19. Absolute environmental impacts of producing 1 kWh of electricity. Datasheet: Electricity, high voltage {ES}| electricity production, wind, 1-3 MW turbine, onshore | Cut-off, U *(EcoInvent)*

Impact Categories	Units	Total
Abiotic depletion	kg Sb eq	6.98E-07
Abiotic depletion (fossil fuels)	MJ	1.53E-01
Global warming (GWP100a)	kg CO_2 eq	1.24E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	8.86E-10
Human toxicity	kg 1,4-DB eq	3.98E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	5.65E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.18E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	5.48E-05
Photochemical oxidation	kg C_2H_4 eq	3.60E-06
Acidification	kg SO_2 eq	5.45E-05
Eutrophication	kg PO_4^{-}-- eq	2.90E-05

In this sense, the impacts attributable to each kg of H_2 generated with the HAEOLUS project technology have been recalculated considering EcoInvent data for a wind farm located in Spain. To do this, it has been considered that the electrolyser operates with the same yields, resource consumptions, productivity, etc. as those detailed in the section on the Raggovidda wind farm. As a result, the impacts obtained are shown in Table 20.

Table 20. Absolute environmental impacts of the production of 1 kg of H_2 in Moncayuelo (estimations based on electrolyser operation: 4 h/day)

Impact Categories	Units	Total	Purified water	Electricity	Wastewater	Maintenance (4 h/day)
Abiotic depletion	kg Sb eq	3.79E-05	9.23E-08	3.77E-05	1.72E-08	1.05E-07
Abiotic depletion	MJ	8.35E+00	7.23E-02	8.25E+00	8.10E-03	1.60E-02
Global warming (GWP100a)	kg CO_2 eq	6.87E-01	5.87E-03	6.70E-01	1.06E-03	9.41E-03
Ozone layer depletion (ODP)	kg CFC-11 eq	1.44E-06	3.29E-09	4.78E-08	3.92E-11	1.39E-06
Human toxicity	kg 1,4-DB eq	2.17E+00	5.83E-03	2.15E+00	2.47E-03	1.30E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.06E+00	4.50E-03	3.05E+00	1.38E-03	4.36E-03
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.28E+03	8.92E+00	2.26E+03	1.70E+00	6.50E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	3.00E-03	1.69E-05	2.96E-03	3.19E-06	1.77E-05
Photochemical oxidation	kg C_2H_4 eq	1.98E-04	2.12E-06	1.94E-04	2.01E-07	7.23E-07
Acidification	kg SO_2 eq	3.00E-03	4.79E-05	2.94E-03	2.73E-06	6.53E-06
Eutrophication	kg PO_4^{-}-- eq	1.58E-03	9.50E-06	1.57E-03	1.18E-06	3.13E-06

In this case study, all impacts have slightly increased compared to the Raggovidda scenario, although the increase is less than 2% in all cases. In terms of GHG emissions, it can be seen that the production of one kg of H_2 emits 0.687 kg CO_2eq, compared to 0.674 kg CO_2eq / kg H_2 obtained in the case of the Raggovidda wind farm (+1.98%) (compression not included) . However, these results should be taken with caution, as a detailed comparison of the two wind farms would require a detailed study based on actual operation data at both sites, which is beyond the scope of this analysis.

Finally, although H_2 reelectrification has not been considered in the Moncayuelo scenario, a short study has been carried out in this report to demonstrate the environmental benefits of generating electricity from wind-generated H_2 in a country other than Norway, with an energy mix that is not entirely based on renewable energies. Among European countries, Spain has an above-average share of renewable energies. By 2021, the share of renewable energies in Spain was close to 47% [21]. The percentage representation of all energy sources involved in the Spanish energy mix is shown in Figure 20.

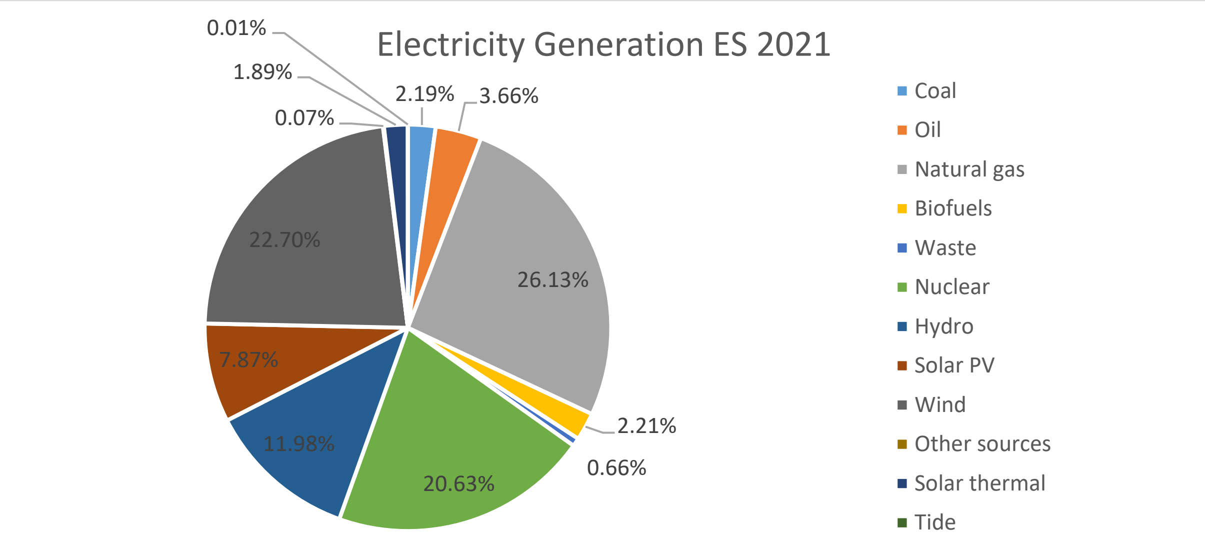

Figure 20. Electricity generation by source in Spain, 2021 [21]

Based on the information available in the figure above, the environmental impacts associated with the production of one kWh with the Spanish electricity mix have been modelled with Simapro and the EcoInvent database. The results obtained are shown in Table 21.

Table 21. Impact of one kWh generated with the Spanish electricity mix, 2021.

Impact Categories	Units	Spanish electricity mix, 2021
Abiotic depletion	kg Sb eq	9.20E-07
Abiotic depletion	MJ	3.78E+00
Global warming (GWP100a)	kg CO_2 eq	2.45E-01
Ozone layer depletion (ODP)	kg CFC-11 eq	2.61E-08
Human toxicity	kg 1,4-DB eq	7.09E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	8.00E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.49E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	8.12E-04
Photochemical oxidation	kg C_2H_4 eq	3.37E-05
Acidification	kg SO_2 eq	5.94E-04
Eutrophication	kg PO_4^{-}-- eq	1.62E-04

Of all the impacts calculated, we are going to analyse again the global warming indicator in more detail due to its current relevance. Taking into account the results of the project, the reelectrification of the H_2 generated in a wind farm such as Raggovidda may produce electricity with GHG emissions ranging from 71.6 g CO_2/kWh to 84.5 g CO_2/kWh, depending on whether the transport of H_2 outside the wind farm is included. if we repeat the same calculation but considering the impacts of electricity from an equivalent Spanish wind farm (Table 20), the emissions from each kWh of electricity generated in a possible fuel cell would be 72.9 and 85.8 g CO_2/kWh respectively. Whether or not the H_2 transport is taken into account, it can be seen that electricity generated by the project fuel cell would be capable of reducing the environmental impact of electricity from the main grid in Spain (245 g CO_2/kWh) by 65-70%. Furthermore, if this same analysis were repeated for other countries with a lower share of renewable energies than Spain, the environmental benefit obtained would be even greater.

Therefore, as a result of this analysis, we can determine that from an environmental point of view, the reelectrification of H_2 generated in wind-powered electrolysers generates a significant environmental improvement with respect to the average impact of the electricity generated in Spain. However, other factors such as technical feasibility, economic profitability, etc. should also be critical aspects to be taken into account for the possible implementation of a system with these characteristics.

6 Conclusions

The main objective of the study presented in this deliverable is to assess the environmental impact of the operation and maintenance (O&M) of the technologies developed in the HAEOLUS project. For this purpose, this study has analysed the environmental impact associated with the hydrogen production through water electrolysis, using the electricity generated from a wind power plant located in Raggovidda, as well as the H_2 reelectrification by means of a fuel cell.

To this end, the LCA methodology, supported by the international standards ISO 14040 and ISO 14044, was used to quantify the environmental impacts of the project's technologies. The study has been carried out with a gate-to-gate scope, paying special attention to the impacts derived from the system's operation and maintenance, and with a double functional unit: on the one hand, the study is referred to each kWh of electricity generated in those scenarios in which the reelectrification of H_2 is considered. On the other hand, each kg of H_2 for those scenarios in which H_2 is sold directly. Besides, the analysis considers results from the pilot plant installed at Raggovidda, as well as simulations performed for the other locations such as Smøla and Moncayuelo. Additionally, the LCA study carried out considers the quantification of the environmental indicators proposed by the evaluation method CML-IA. Among these indicators, the global warming indicator has been analysed in more detail throughout this study.

The main findings of this study are listed below:

- In the scenario where H_2 is used as fuel, impacts associated to each kg of H_2 would change depending on the number of hours of operation of the electrolyser. In the case of the electrolyser running 4 hours per day, the impacts of each kg of H_2 are shown in Table 22. Most of the environmental impact is generated by the electricity consumption of the water electrolyser and therefore, the source of electricity is a key factor in the impact of the produced H_2.

Table 22. Absolute environmental impacts of the production of 1 kg of H_2 (electrolyser production: 4 h/day), with and without compression and storage

Impact Categories	Units	H_2 production	H_2 (production + compression)
Abiotic depletion	kg Sb eq	3.72E-05	3.97E-05
Abiotic depletion	MJ	8.19E+00	8.74E+00
Global warming (GWP100a)	kg CO_2 eq	6.74E-01	7.19E-01
Ozone layer depletion (ODP)	kg CFC-11 eq	1.44E-06	1.44E-06
Human toxicity	kg 1,4-DB eq	2.13E+00	2.27E+00
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.00E+00	3.21E+00
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.23E+03	2.38E+03
Terrestrial ecotoxicity	kg 1,4-DB eq	2.94E-03	3.14E-03
Photochemical oxidation	kg C_2H_4 eq	1.94E-04	2.07E-04
Acidification	kg SO_2 eq	2.94E-03	3.14E-03
Eutrophication	kg PO_4^{-}-- eq	1.55E-03	1.66E-03

- The results obtained have been compared with other studies published in the literature and were found to be in agreement with the results of other authors. The most common method of H_2 production is through the methane reforming process. In this process, it is estimated that about 11.5 kgCO_2eq/kg H_2 are generated. Therefore, the production of green H_2 from wind energy generates a GHG emission saving of 94%.

- In the case of H_2 reelectrification in a fuel cell, the environmental impacts attributable to each kWh of electricity produced are shown in Table 23, whether or not the impact associated with H_2 transport is taken into account.

Table 23. Absolute environmental impact of producing 1 kWh of electricity from H_2 in a fuel cell (reelectrification), with and without H_2 transport

Impact Categories	Units	Impacts per kWh (including H_2 transport)	Impacts per kWh
Abiotic depletion	kg Sb eq	4.03E-06	3.94E-06
Abiotic depletion	MJ	1.05E+00	8.69E-01
Global warming (GWP100a)	kg CO_2 eq	8.45E-02	7.16E-02
Ozone layer depletion (ODP)	kg CFC-11 eq	1.45E-07	1.43E-07
Human toxicity	kg 1,4-DB eq	2.32E-01	2.26E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.23E-01	3.19E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.46E+02	2.37E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	3.36E-04	3.12E-04
Photochemical oxidation	kg C_2H_4 eq	2.21E-05	2.06E-05
Acidification	kg SO_2 eq	3.42E-04	3.12E-04
Eutrophication	kg PO_4^{-}-- eq	1.81E-04	1.65E-04

- A comparison of the impacts attributable to each kWh of electricity produced with the fuel cell with the impacts of the Norwegian electricity mix shows that the impact of each kWh generated from green H_2 reelectrification is significantly higher than the impact of electricity produced from the Norwegian energy mix (19.6 g CO_2eq vs. 71.6 -84.5 g CO_2eq). However, this is due to the fact that Norway is one of the cleanest energy countries in Europe. If we compare the results with the impact of the electricity mix in Spain (which has a high share of renewable energies but less than Norway), we obtain that the electricity generated by the HAEOLUS project fuel cell would be able to reduce the environmental impact of electricity from the main grid in Spain (245 g CO_2/kWh) by 65-70%.

7 References

[1] S. Shiva Kumar and V. Himabindu, "Hydrogen production by PEM water electrolysis – A review," *Mater Sci Energy Technol*, vol. 2, no. 3, pp. 442–454, 2019, doi: https://doi.org/10.1016/j.mset.2019.03.002.

[2] P. Nikolaidis and A. Poullikkas, "A comparative overview of hydrogen production processes," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 597–611, 2017, doi: https://doi.org/10.1016/j.rser.2016.09.044.

[3] M. Delpierre, J. Quist, J. Mertens, A. Prieur-Vernat, and S. Cucurachi, "Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis," *J Clean Prod*, vol. 299, p. 126866, 2021, doi: https://doi.org/10.1016/j.jclepro.2021.126866.

[4] International Organization for Standardization, *UNE-EN ISO 14040:2006 - Environmental management- Life Cycle Assessment- principles and framework*. 2006.

[5] International Organization for Standardization, "ISO 14044:2006, Environmental management -- Life cycle assessment -- Requirements and guidelines," 2006.

[6] Directorate-General for Environment, "Recommendation on the use of Environmental Footprint methods," 2021. https://ec.europa.eu/environment/publications/recommendation-use-environmentalfootprint-methods_en (accessed Jul. 06, 2022).

[7] K. Lundmark and S. McGowan, "Electricity, steam and hot and cold water generation and distribution. Product Category Rules (PCR)," Stockholm, Sweden, 2021. [Online]. Available: http://www.environdec.com/PCR/Detail/?Pcr=5802

[8] M. Santos, R. Rodríguez, S. García, S. Damman, and U. Johansen, "D5.3. Techno-economic analysis of wind- hydrogen integration," 2020. Accessed: Jan. 18, 2023. [Online]. Available: https://cordis.europa.eu/project/id/779469/results

[9] I. Marino and M. Santos, "D8.1. Protocols for demonstration of energy-storage strategy," 2020. Accessed: Jan. 18, 2023. [Online]. Available: https://cordis.europa.eu/project/id/779469/results

[10] E. García and M. Santos, "D8.2. Protocols for demonstration of mini-grid strategy," 2020. Accessed: Jan. 18, 2023. [Online]. Available: https://cordis.europa.eu/project/id/779469/results

[11] E. García and M. Santos, "D8.3. Protocols for demonstration of fuel-production strategy," 2021. Accessed: Jan. 18, 2023. [Online]. Available: https://cordis.europa.eu/project/id/779469/results

[12] INGRID project, "High-capacity hydrogen-based green-energy storage solutions for grid balancing," 2016. https://cordis.europa.eu/project/id/296012 (accessed Jan. 09, 2023).

[13] A. Agostini *et al.*, "Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units," *Appl Energy*, vol. 215, pp. 1–12, Apr. 2018, doi: 10.1016/j.apenergy.2018.01.095.

[14] A. Hoskin *et al.*, “Task 24: Wind Energy and Hydrogen Integration—Final report.,” 2013.

[15] D. Candelaresi, A. Valente, D. Iribarren, J. Dufour, and G. Spazzafumo, “Comparative life cycle assessment of hydrogen-fuelled passenger cars,” *Int J Hydrogen Energy*, vol. 46, no. 72, pp. 35961–35973, Oct. 2021, doi: 10.1016/j.ijhydene.2021.01.034.

[16] IEA, “The future of hydrogen,” *International Energy Agency report*, 2019.

[17] C. Bauer *et al.*, “On the climate impacts of blue hydrogen production,” *Sustain Energy Fuels*, vol. 6, no. 1, pp. 66–75, Jan. 2022, doi: 10.1039/d1se01508g.

[18] K. de Kleijne, H. de Coninck, R. van Zelm, M. A. J. Huijbregts, and S. v. Hanssen, “The many greenhouse gas footprints of green hydrogen,” *Sustain Energy Fuels*, vol. 6, no. 19, pp. 4383–4387, Aug. 2022, doi: 10.1039/d2se00444e.

[19] Z. S. Chen and J. S. L. Lam, “Life cycle assessment of diesel and hydrogen power systems in tugboats,” *Transp Res D Transp Environ*, vol. 103, Feb. 2022, doi: 10.1016/j.trd.2022.103192.

[20] K. Bareiß, C. de la Rua, M. Möckl, and T. Hamacher, “Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems,” *Appl Energy*, vol. 237, pp. 862–872, Mar. 2019, doi: 10.1016/j.apenergy.2019.01.001.

[21] IEA - International Energy Agency, “IEA Electricity Information 2022,” 2022. https://www.iea.org/data-and-statistics/data-product/electricity-information (accessed Jan. 17, 2023).