PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

D1.2

First version of the H_2 releases' database

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EXECUTIVE SUMMARY

To date no inventory of hydrogen (H_2) emissions occurring along the value chain exists. Otherwise, few data are publicly available. Due to its potential impact on Global Warming Potential, in recent years more attention was given to the estimation of H_2 emission (Cooper et al., 2022; Derwent, 2023). Waiting for a conclusive answer about its impact on the atmosphere, some contributions appear in the literature providing some inputs (Arrigoni et al., 2024; Bond et al., 2011; Frazer-Nash Consultancy, 2022; Sand et al., 2023). However, due to the relevance of the topic, a rigorous approach defining how to collect data is needed as soon as possible.

The NHyRA project aims to be the starting point. However, several considerations arose during the first six months of activity regarding the inventory design. First, the methodology accepted in the natural gas (NG) should be considered a first template for H_2. Therefore, defining new terminology or emission classification would not be necessary. This choice could simplify any standardization activity. Three types of emissions, i.e., fugitives, vented, and incomplete combustion, were adopted. As for the NG case, sub-categories were also identified to ensure proper categorization. Secondly, the inventory has to be designed to collect data regarding the emissions from each archetype defined in Task 1.1. The data selection is of paramount importance to ensure a proper characterization of the emissions and allow for the achievement of other target activities by the interested end-users, such as scenario analysis and mitigation analysis. During the task activity, the discussion among the involved partners of the NHyRA project achieved an agreement to record the parameters that were considered relevant. Due to the high amount of information to be recorded, the NHyRA partners also agreed to develop this manual to explain the philosophy on which it is based on the inventory.

Since it is expected to get new data during the NHyRA project and after its completion, rules have been defined to ensure the quality of the data to be inserted in the inventory. As reported the quality check will consist in a rigorous procedure ensuring the traceability of the source for future validation or replication especially in the case of experimental value.

The NHyRA project partners identified some limitations of the present study to direct the research in the next months. First, the present version of the H_2 inventory includes a limited amount of data for some of the archetypes in the H_2 value chain section, including production, conversion, storage, transport, and end-uses. More data are needed to ensure consistent scenario analysis and provide mitigation action recommendations. The new inventory releases at M12 and M18 are expected to achieve the target. For this purpose, the literature review has to be improved. Second, the NG approach adopted in the present study relies not only on the direct measurement of the emission but also on emission factors. Concerning the direct measurement, the emission factor needs other parameters to estimate the emission, i.e., the “activity factors”. Specifically, dedicated formulas are required to calculate the total emission, which can also be derived from experience in the field or, more in general, from the experts' know-how (see section 4.15). Due to the complexity and the need to be in contact with the experts in the Consortium, the NHyRA partners agree to discuss more in detail the development of the correlations and of the activity factors that will also be used in WP4 for scenario analysis and to publish the first results in M12 and, finalize them at M18 in accordance with the progress of Task 1.4 and WP4.

GLOSSARY

Archetype
A schematic and standardized representation of a process or of an equipment as defined below.

Activity factor (AF)
Numerical value describing the size of the population of emitting equipment such as length of pipelines, number of valves (per type), number of pneumatic devices (per type), or the number of emitting events such as number of operating vents, multiplied, if relevant, by the duration of the emission.

Component
Part or element of a larger whole, e.g., flange, valve, connection.

Continuous emission
An emission that occurs continuously without any interruption. However, the magnitude of the emission could change due to ageing or other degradation phenomena.

Device
Equipment (active or passive) related to a hydrogen (H_2) system and needed in order to keep the normal operation of the system.

Discontinuous emission
An emission that occurs in the case that a specific event occurs and that lasts for a limited period of time.

Equipment
Asset, device or component of a hydrogen system depending on the considered granularity.

Emission factor (EF)
Factor that describes typical H_2 emissions of a component or part of the system (e.g., valve, pipeline section) or from an event and can have units like [kg/km] or [kg/event].

Fugitive emission
Leakages due to tightness failure and permeation.

Hydrogen emission
Intentional or unintentional release of H_2 to the atmosphere, whatever the origin, reason and duration.

Hydrogen system
Any plants or, more generally, archetypes defined in Task 1.1 and implemented in a H_2 supply chain section, e.g., production, storage, conversion, transportation and end uses.

Hydrogen supply chain
The system of activities from suppliers to customers including hydrogen production, storage, conversion, transport and end-uses.

Incident
Unexpected occurrence, which could lead to an emergency situation.

Incident emission
Hydrogen emissions from unplanned events.

Incomplete combustion emission
Unburned hydrogen in the exhaust gases from natural gas combustion devices, such as turbines, engines, boilers or flares.

Operational emission
Hydrogen emissions from normal or planned operating activities.

Permeation
Penetration of a permeate (such as a liquid, gas, or vapour) through a solid.

Site
All sources within a physical unit. A site can be a steam methane reforming plant, an electrolysis plant, a compressor station, a hydrogen pipeline segment, liquified hydrogen terminal, a storage plant, etc.

Source
Component within a process or equipment that releases H_2 to the atmosphere either intentionally or unintentionally, intermittently or continuously.

Vented emission
Gas released into the atmosphere intentionally from processes or activities that are designed to do it, or unintentionally when equipment malfunctions or operations are not normal.

Venting
Operational release of gas into the atmosphere.

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1. Introduction

To date, no database about hydrogen (H_2) emissions occurring along the value chain exists. However, correct and validated data would be of paramount importance to rigorously perform scenario analysis and provide recommendations to interested stakeholders on how to implement effective mitigation strategies.

Since the research community began the investigation only recently, no standardized methodology exists in data collection and utilization. Therefore, due to similarities between the two sectors, the NHyRA partners agreed to start the design of the inventory by the adoption of the same approach used in the natural gas (NG) sector as reported by Marcogaz (Marcogaz, 2018, 2019). This choice was also justified by the fact that NG methodology to estimate NG emissions along the supply chain has obtained a quite large consensus among the involved stakeholders. Therefore, the NHyRA partners believe that the adoption of the same methodology would make future standardization processes easier and faster.

Regarding the level of detail adopted, it has to be highlighted that while for methane emissions international initiatives have started, nothing of similar has occurred for the H_2 sector yet. Among the initiatives in NG, the Oil and Gas Methane Partnership (OGMP) can be considered as a reference (OGMP 2.0, 2024). The OGMP 2.0 is a multi-stakeholder partnership that brings together oil and gas companies as well as international organisations - governments and non-governmental - to improve the accuracy and transparency of reporting of methane emissions. Specifically, OGMP 2.0 is a measurement-based reporting framework with five increasing levels of detail (see Figure 1).

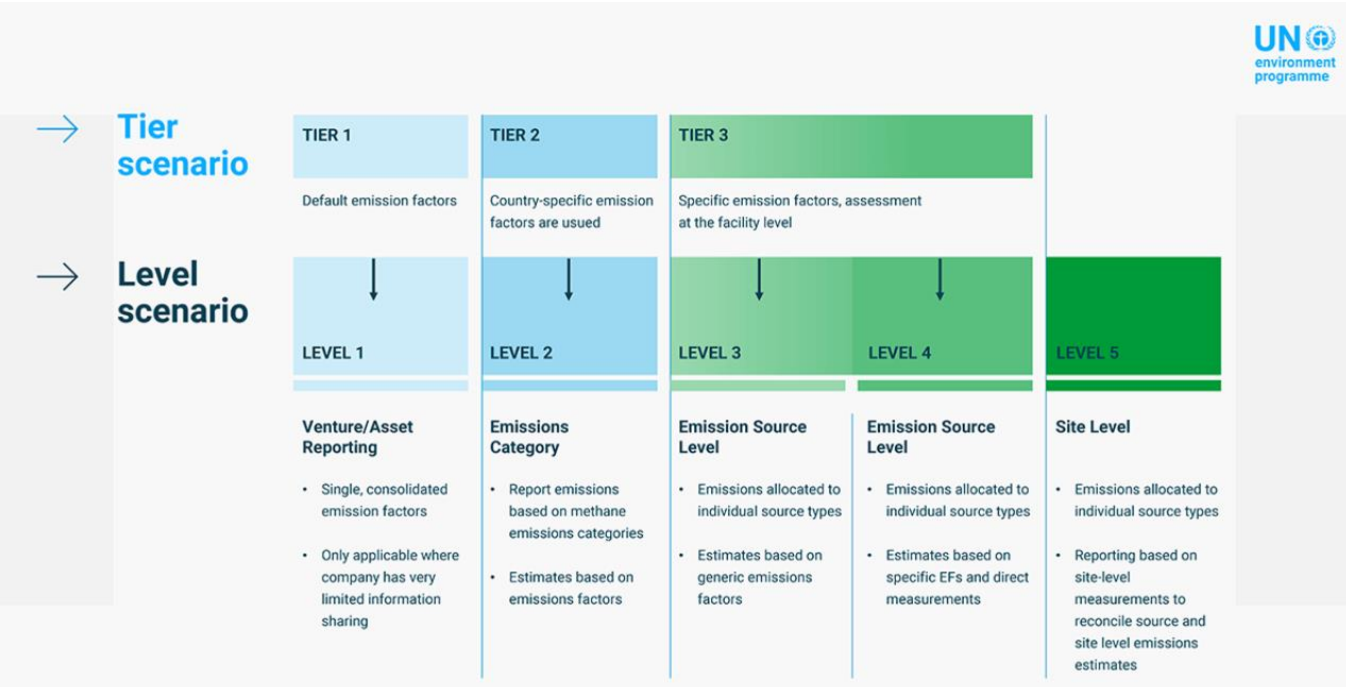

Figure 1. OGMP 2.0 and tier correspondence. Source: (OGMP 2.0, 2024).

Even if the scenarios analysis in the NHyRA project is expected to reach at least Tier 2 or, equivalently, to Level 2 of the OGMP 2.0., the inventory should be structured in order to allow a greater granularity up to single devices or components. If the case, NHyRA consortium will discuss to incorporate level 3 emission factors after the tests.

The structure of the inventory has been designed by assuming that the quantification of H_2 sources will be performed through a source-level method of quantification making it possible for the interested stakeholders to apply different levels of detail depending on their needs and expectations. More specifically, this method consists in splitting the H_2 value chain into groups of assets, devices and components and indicating categories of emission that can be expected from these groups. The final amount of H_2 emissions will be calculated by summing up all the emission that can be measured, estimated based on existing knowledge and statistics, or calculated from existing and applicable correlations.

Several challenges have been encountered and overcome in the realization of the inventory. First, the archetypes defined in Task 1.1 are usually characterized by a high customization that depends on the specific applications and requirements from the customers. Therefore, at the current stage of the project, the ranges of values indicated in the inventory refer to generic plants/components when no more detailed information is available. On the other hand, the specific boundary conditions that apply are indicated. Secondly, due to the complexity of the topic, the inventory is in a preliminary version that will be updated at least every six months with new data deriving from direct measurements by project partners, from the literature, and the addition of validated and universally accepted correlations for H_2 emissions.

2. Methodology

This section describes the methodology adopted for the design of the H_2 emission inventory. As shown in Figure 2, the procedure to design and update the inventory includes several steps. A brief description is provided in the following sections.

The inventory has the goal to collect data that could allow the estimation of H_2 emissions of any possible supply chain in which the archetypes defined in Task 1.1 can be present. For more details, the Deliverable D1.1 has to be considered as a reference. NHyRA partners involved in Task 1.2 agreed for the preliminary structure of the inventory as shown in this deliverable. Once the structure had been agreed, the data collection started. Two different sources of data are considered to populate the database: experimental measurement, literature review, and NHyRA partners' know-how. The update of the inventory with new data will be continuous until the end of the project. Furthermore, contributions from people external to NHYRA Consortium are welcomed. Therefore, a procedure to perform a quality check was discussed and approved in the NHyRA Consortium (see 2.2).

The next paragraphs describe:

1. A focus on the activities of Task 1.2 until M6;
2. The rule adopted by the NHyRA Consortium to ensure a proper quality check before updating the inventory with new data;

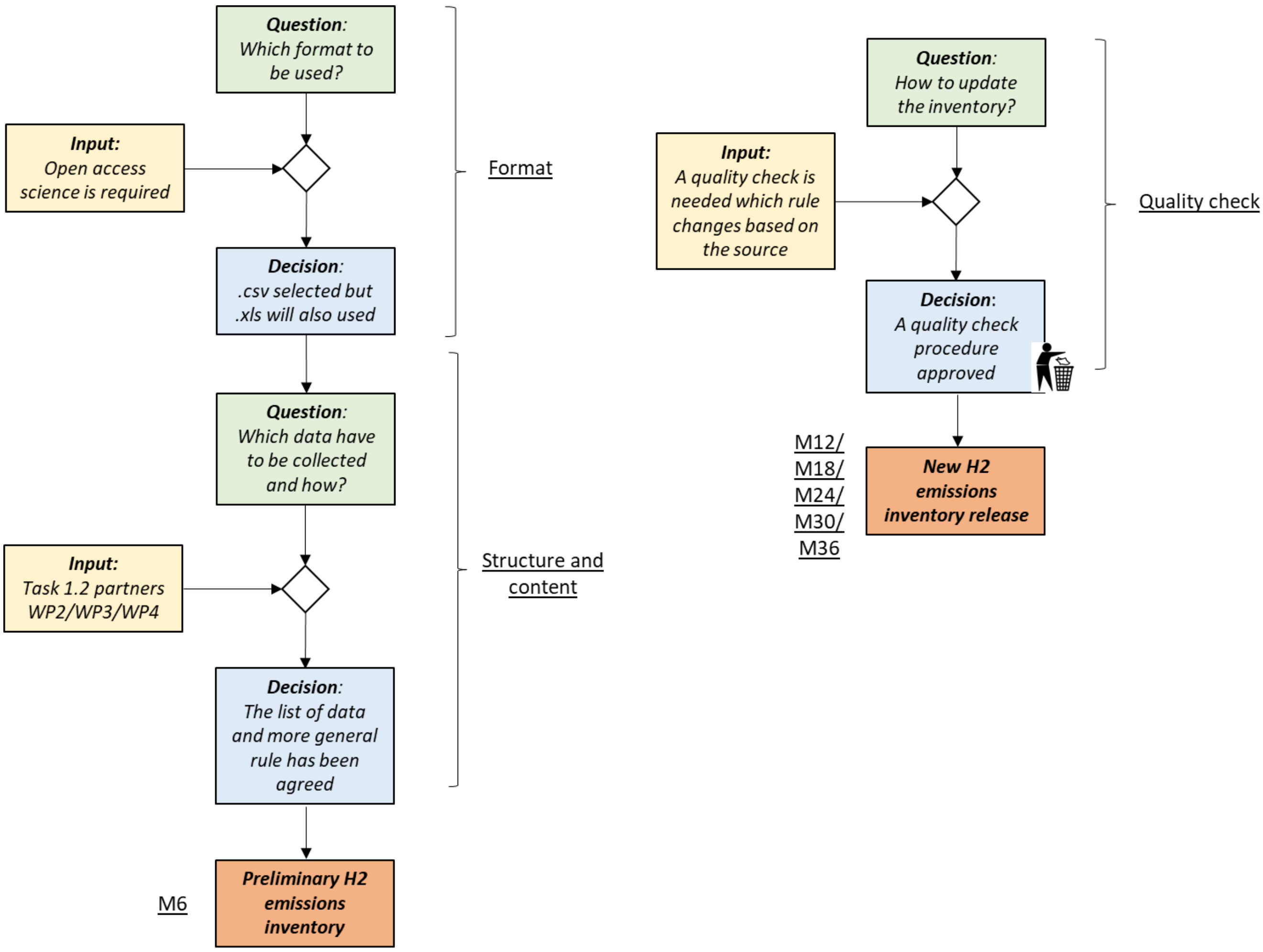

Figure 2. Inventory design and update procedure.

2.1. H2 emissions inventory structure – preliminary design

This section reports on the activities performed by the NHyRA Consortium until M6. Therefore, the decisions could be reviewed if required in the next releases of the inventory.

Inventory format

The NHyRA partners agreed to adopt ".pdf", ".xls" and ".csv" formats to ensure open access science and share the content of the inventory.

Inventory structure

The structure of the inventory was designed considering the following questions:

Q1: *Which data have to be collected to make the inventory useful for the purpose of the NHyRA project and, more generally, to those who want to estimate the emissions along any possible H_2 supply chain*?

To answer the question, inputs from other WP leaders were considered. In fact, several connections exist among WP1 and other WPs as shown in Table 1. For instance, the data generated in WP3 will be introduced in the inventory. Similarly, the inventory will provide outputs to WP2 and WP4; WP2 will design the methodology based on the data to be collected. WP4 will perform scenario analysis by using the data available in the inventory.

Table 1. Links with the other work packages.

Input / Output	Comments
Output to WP2	WP2 will receive feedback from the inventory about the archetypes that need to be characterized.
Input from WP3	WP1 will receive experimental data from the WP3.
Output to WP4	WP4 will use the data included in the inventory to perform scenario analysis

Q2: *How data should be collected and presented to the users?*

To answer this question, the NHyRA partners made the decisions indicated in Table 2.

Table 2. Motivating reasons for data collection and presentation.

Decision	Motivations
The approach used in NG sector for the quantification of emissions in the supply chain is adopted.	This approach was already validated and standardization is ongoing. Furthermore, NHyRA partners agreed on the fact that H_2 supply chains are similar to NG supply chains and could benefit from this standardization.
As much as possible data should be indicated for every data point found in literature.	It would allow the investigation of possible trends.
Where it is possible, the use of pre-defined drop-down lists of values should be preferred to blank cell.	The use drop-down lists should reduce errors and help standardization.
In the case that the H_2 emission occurs at the connection between two archetypes in the supply chain, clear rules have to be defined for its attribution.	The double counting of the emissions has to be avoided.

2.2. Updating procedure

The update of the inventory has to be ensured during the entire duration of the NHyRA project. To ensure the effectiveness of the process, the partners involved in Task 1.4 will be asked to contribute to the update and to the quality check of the new data. The coordination and the periodic verification of the progress will be ensured by Task 1.4 and WP1 leaders.

The inventory will be continuously updated with new data throughout the NHyRA project to enhance our understanding and minimize uncertainties, resulting in more accurate analysis. NHyRA partners will analyse existing documentation and gather new data through planned experimental testing and measurement to reach the goal.

As long as they align with the structure outlined in Section 4, contributions from external sources will be welcomed. However, following a rigorous procedure is essential to ensure high-quality data. Therefore, a quality check will be conducted to verify the new data, with the specific procedure determined by the data source/origin, as outlined in Table 3. Specifically, in the case of a negative check, the reviewer will inform the contributor, i.e., who provided the new data, about the results of the quality check.

Table 3. New data quality check procedure.

Data source	Responsible for the quality check (*)	Quality check	"Positive check" case	"Negative check" case
From the literature	At least one partner of the Consortium	The data will be checked with that indicated in the source	No further actions will be required until the final approval by the NHyRA consortium	Mismatch or impossibility to verify the data source
From measurement	At least two partners of the Consortium	The scientific rigorousness of the measurement will be assessed, including the methodology, and measuring devices used	No further actions will be required until the final approval by the NHyRA consortium	Methodology unclear; no sufficient data about the measuring devices and measurement conditions

A quality check receipt will be provided at the end of the process by the person(s) responsible for the review. The receipt will not be published but will be maintained within the Consortium for the subsequent inventory updating steps. The quality check receipt will include information such as:

- Name of the responsible for data quality check
- Date of the quality check
- Name of the contributor
- Type of data source
- Quality check: APPROVED / NOT APPROVED
- Motivations/note

All the new data and quality checks will be collected by GERG, which is responsible for managing the H_2 emission inventory during the project. The new validated data will not be automatically uploaded to the inventory until the approval of the NHyRA Consortium.

A list of the proposed additions and quality check receipt will be sent to all the partners at least fifteen days before the first available Consortium meeting. The approval or denial will be confirmed during the Consortium meeting. In the case of one or more members not approving the release of the updated version, it should be motivated to GERG within fifteen days. If no comments are received by GERG in due time, it will assume the partners' approval.

Additionally, if the NHyRA consortium would like to change the structure of the inventory, a discussion will be initiated. A list of proposed changes will be circulated to all NHyRA partners at least fifteen days before the first available Consortium meeting. The approval or the denial of the changes will be confirmed during the Consortium meeting. If all the partners agree with the proposed change, it will be published in the new release of the inventory. In the case one or more partners do not approve the release of the updated version, it should be motivated. If no comments arrive until fifteen days from the Consortium meeting, the partners' approval will be assumed.

3. Abbreviations

The present section indicates the abbreviations used in the deliverable as shown in Table 4. The abbreviations section will be updated every time a new release will be published with new terms. Furthermore, it was decided to not include in this release a table for symbols due to their limited number in the text. Since it is expected that a relevant number will be identified in the future, the table will be reported in the next releases.

Table 4. Abbreviations adopted in the deliverable.

Abbreviations	Description
AF	Activity factor
EF	Emission factor
H_2	Hydrogen
M	Month
NG	Natural gas
OGMP	Oil and Gas Methane Partnership
WP	Work Package

4. Structure of the H_2 emissions' inventory

In this preliminary release, the inventory includes the data indicated in Table 5. As shown, the NHyRA partners agreed to collect the following data for each emission. In the following section, the explanation of each data is reported in the paragraphs 4.1-4.16. For the sake of clarity, an example on how data has to be collected is provided. The example is related to the boil-off occurring in liquid H_2 storage tanks.

Table 5. Structure of the H_2 emissions' inventory.

Column	Term
A	Macro category
B	Archetype
C	Type of emission
D	Category of emission
E	Sub-category of emission
F	Emission equipment - description
G	Temporal profile of the emission
H	H_2 Concentration
I-N	Relevant parameters
O	Data source level
P	Literature reference (if applicable)
Q	Value of H_2 emission / Emission factor
R	Unit of measurement
S	Measurement conditions (if applicable)
T	Correlations for the estimation of the H_2 emission from EF (if applicable)
U	Notes

4.1. Macro-category

In accordance with the categorization proposed in the Task 1.1, the "macro-category" field refers to the main categories that are present in the H_2 value chain and that include all the stages through which it is possible to investigate any type of supply chain. Specifically, the macro-category has to be selected among the following five textual values that represent specific parts of the H_2 supply chain while other values will be not allowed:

1. Production;
2. Conversion / reconversion;
3. Storage;
4. Transport;
5. End-uses.

Example: boil-off from liquid H_2 storage tanks

The value "Storage" has to be selected from the drop-down list since the archetypes from which the emission occurs belongs to this specific section of the supply chain.

4.2. Archetype

As detailed described in D1.1, each macro-category includes several processes/archetypes to manage H_2 as shown in Figure 3. Therefore, it is essential to identify the corresponding archetype to perform scenario analysis. For this purpose, this field specifies to which of the archetypes shown in the figure refers the H_2 emission.

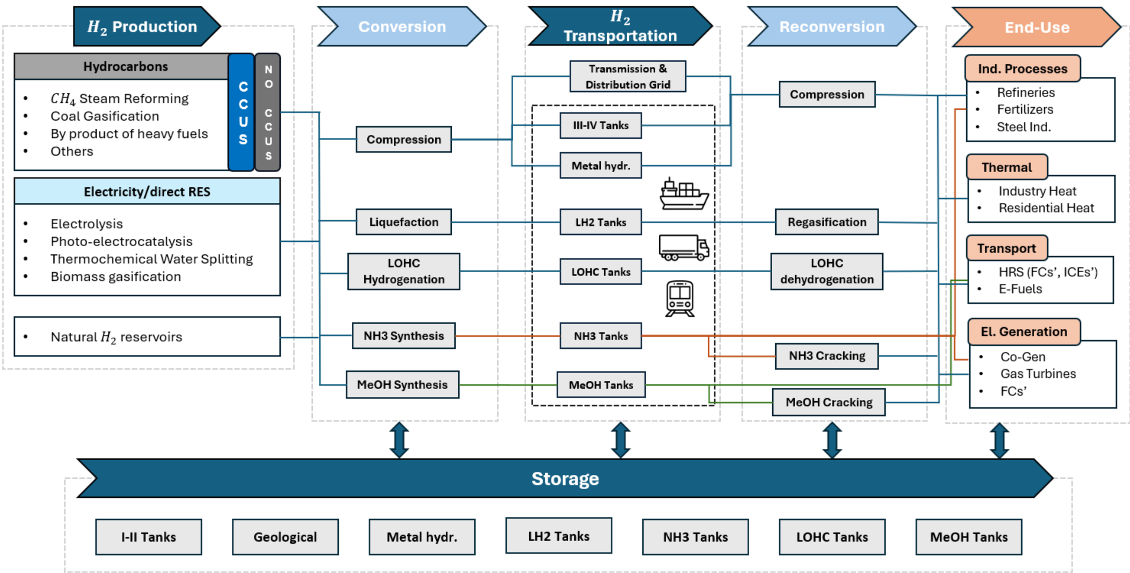

Figure 3. H_2 supply chains and evaluated technologies for NHyRA.

<u>Example: boil-off from liquid H_2 storage tanks</u> The value "LH_2 Tanks" has to be selected from the drop-down list.

4.3. Type of emission

In accordance with the NG sector's approach, H_2 emissions are categorized in three types of emissions:

- Fugitive emission. These emissions include leakages due to tightness failure and permeation.
- Vented emission. These emissions are those released into the atmosphere intentionally from processes or activities that are designed to do it, or unintentionally when equipment malfunctions or operations are not normal.
- Incomplete combustion. It refers to unburned H_2 in the exhaust gases from combustion devices, such as turbines, engines, boilers or flares.

<u>Example: boil-off from liquid H_2 storage tanks</u> The boil-off is responsible for H_2 evaporation and for an increase of the pressure in the tank. When the pressure reaches the set point of the relief valve, H_2 is discharged into the atmosphere. For this reason, the boil-off is categorized as "Vented emission".

4.4. Category of emission

Each H_2 emission type is further divided in several categories depending on the source. As for the previous field, also for the category of emission, the NG approach has been adopted. The categorization indicated in Table 6 is used in the inventory.

<u>Example: boil-off from liquid H_2 storage tanks</u> In the case of emission due to boil-off, entering into the table two options are available: "Operations" and "Incident". Since the value "Incident" refers only to events not predictable during operation, "Operations" should be selected.

4.5. Sub-category of emission

For some emissions, further details are required. Specifically, more details are needed for those categories that include several modes of emissions as shown in Table 6.

Example: boil-off from liquid H_2 storage tanks

In the previous step, the boil-off emission has been classified in the category "Operations". Five different options are available as subcategory to detail the emission: i) Purging/venting for works, process, commissioning and decommissioning, ii) Regular emissions of devices, iii) Starts & stops, iv) Leaks due to unexpected, sudden changes in conditions, and v) Boil off – evaporation. In the example, the selection should be "Boil off – evaporation".

Table 6. H_2 emissions per category. A not exhaustive list of examples is reported in the right column.

H_2 emissions			
Types of emissions	**Category**	**Subcategory**	**Examples (not exhaustive)**
Fugitives	Leaks due to connections/loss of tightness	Leaks typically due to gradual changes in conditions	Leaks of flanges, seals, joints, valve seats
	Permeation	Wall permeation	Emissions from tanks or pipeline wall
		Subsurface emissions from a storage reservoir to the atmosphere	Emission from reservoir
Vented	Operations	Purging/venting for works, process, commissioning and decommissioning	Works, maintenance, renewal
		Regular emissions of devices	Pneumatic emissions actuators, flow control valves, measurement equipment, compressor seals…
		Starts & stops	Emissions from start and stops of compressors
		Leaks due to unexpected, sudden changes in conditions	Leaks due to third party damage, construction defect/material failure, ground movement
		Boil off - evaporation	Leaks due to overpressure caused by evaporation of liquid H_2
	Incidents	Leaks due to unexpected, sudden changes in conditions	Leaks due to third party damage, construction defect/material failure, ground movement
Incomplete combustion			Unburned H_2 in exhaust gases from combustion devices

4.6. Emission equipment - description

This data has to be filled in by the user specifying the source of the emission. This data is particularly useful in the case the exact origin of emissions is known, allowing to ensure a higher level of detail.

Example: boil-off from liquid H_2 storage tanks

In the example, since the emission detail refers to the LH_2 tank, it can be simply indicated "Tank".

4.7. Temporal profile of the emission

The temporal profile specifies how the H_2 emissions is expected to occur in the period of analysis. It will be important to consider this information when the total H_2 emission will have to be calculated. Three values can be indicated in the inventory:

- Continuous emission, i.e., the H_2 emission is insensitive to time and it occurs continuously (i.e., 24h/24h)
- Discontinuous emission. The H_2 emission occurs for specific periods of time that have to be clearly identified for the correct estimation of the total amount of H_2 emission.
- Continuous and Discontinuous emission. In some case, a total value is required including both types of emission. It could be the case of the total emission value of a site where it is not possible to distinguish between the two cases.

Example: boil-off from liquid H_2 storage tanks

In the example, since the relief valve opens periodically, the user has to select "Discontinuous emission".

4.8. H_2 Concentration / Composition of the emission

In some cases, H_2 emissions is mixed with other gases, e.g., flue gases from combustion. Therefore, in all the cases where H_2 is mixed with other gases, the contribution can be calculated as the product between its concentration and the mixture volumetric flowrate.

In the inventory the exact H_2 concentration in %vol. has to be indicated. Furthermore, the list of species, i.e., the composition of the gases including water vapour, should be indicated (if available).

Example: boil-off from liquid H_2 storage tanks

In the example, since the relief valve discharges only pure H_2, the user can indicate 100%vol. H_2.

4.9. Relevant parameters for the estimation of the emission

The amount of H_2 emission is influenced by many factors that differ among the archetypes. The identification of these parameters is a complex task that will continue through the entire duration of the NHyRA project and will benefit from the inputs received by the Consortium and from the stakeholders in the Advisory Board.

Example: boil-off from liquid H_2 storage tanks

The parameters indicated in Table 7 have been preliminary considered relevant for the quantification of H_2 emissions due to the boil-off of liquid H_2 storage tanks. If the values of these parameters are available, they should be indicated together with the emission.

Table 7. Parameters for H_2 emissions quantification.

H2 content [ton]	Volume [m³]	Demand profile and application (long term storage / HRS)	Service life [years]	Type of insulation	Installation (vertical/horizontal), (Above ground/underground)

4.10. Data source level

The data source refers to the origin of the data reported in the inventory. Three sources of data can be selected:

1. Directly measured.
2. Experimental values reported in the literature
3. Other estimations

4.11. Literature reference (if applicable)

The literature reference has to be indicated for secondary level and third level data sources. In the case of primary level data source, it has to be indicated "Not Applicable".

4.12. Value of the emission / Emission factor (if applicable)

The data refers the value to be used to quantify H_2 emissions along the supply chain. In fact, the quantification of the H_2 emission comprises i) measurements of the amount of H_2 emitted from different origins), ii) estimation of emissions from groups of assets or calculation based on available data (third level source).

4.13. Unit of measurement

To avoid misunderstanding, the unit of measurement to which the value refers has to be clearly indicated. The International System of Units has to be preferably used. If a different system is adopted, it has to be motivated and explained in the note.

4.14. Measurement conditions (if applicable)

In the case that primary or secondary data source levels are selected, the methods and the materials adopted for the measurement should be declared to ensure the repeatability of the test. Specifically, the following data should be indicated if available:

- Instrumentation used (model and manufacturer)
- Test operating conditions, including any relevant technical standard

In the case of third level data source, it has to be indicated "Not applicable".

4.15. Correlations for the estimation of the H_2 emission from EF

In the case of an estimation the correlation used to quantify the H_2 emission is indicated in this field. During the project, several correlations will be developed in synergy between Task 1.4, WP2, WP3 and WP4, based on the knowledge of the experts in the NHyRA Consortium and in the Advisory Board.

Example: boil-off from liquid H_2 storage tanks

The emission due to boil off from a LH2 tank is calculated through the following equations:

$$E = M_{H2} \times EF \times AF$$

$$AF = time_{storage} \times f_{boil\text{-}off}$$

Where:

E is the total annual emission in [kg/year], M_{H2} is the mass of H2 contained in the storage in [kg], EF is the emission factor, i.e., the H_2 release to the atmosphere as a proportion of nominal mass of the storage, in [%/day] and, AF is the activity factor defined as the product between the number of storage days in a year ($time_{storage}$) in [days/year] and a mitigation factor ($f_{boil\text{-}off}$, %) which value depends on the final utilization of the boil-off, i.e., recovered and liquified, burned in a flare, emitted directly in the atmosphere.

4.16. Notes

Any additional information useful to the description of the H_2 emissions are indicated.

5. Preliminary list of emissions

In this paragraph the list of H_2 emission sources identified in Task 1.1 is indicated for each archetype. In the present release, only a qualitative indication is provided. Furthermore, only those archetypes characterized by a sufficient maturity, i.e., commercially available at industrial scale, and for which relevant information are available, are indicated from Table 8 to Table 12. In fact, few data are available while more data are expected in the next future during the progress of experimental activities developed by the project. It has also to be highlighted that in the case of new information, the data reported in the table below will be updated in the next release of the inventory that will include also this manual. Furthermore, even if not shown, accidents responsible for H_2 emissions into the atmosphere are included in the vented emissions.

5.1. H_2 production

In the present section, a preliminary list of emissions sources for the archetypes belonging to H_2 production is provided in Table 8. As shown, the analysis is limited only to the current mature technologies identified in D1.1:

- Steam methane reforming
- Coal gasification
- By product of heavy fuel cracking
- Water electrolysis
- Biomass gasification

Table 8. Preliminary qualitative list of the emission sources for the archetypes developed in Task 1.1 referred to H_2 production.

Archetype	Fugitive emissions	Vented emissions	Incomplete combustion
Steam Methane Reforming (SMR)	• Continuous emissions through connection fittings, flanges, valves, etc. • Continuous emissions due to permeation	• Release of pressure safety valves release[1]	• Unburned gases
Coals gasification	No relevant differences compared with the emission sources identified for SMR.		
By-product of heavy fuel cracking	No relevant differences compared with the emission sources identified for SMR.		
Water electrolysis	No relevant differences compared with the emission sources identified for SMR.	• Release of pressure safety valves[1] • Purging of cathode line for start-up and shutdown • Contamination of vented oxygen due to crossover • H_2 treatment unit losses • H_2 drying and deoxygenating losses in demister • H_2 venting at start-up and shutdown	Not applicable
Biomass gasification	No relevant differences compared with the emission sources identified for SMR.		
[1] Attention has to be given to avoid double-counting. In some applications, the vents and the discharge of pressure safety valves are directed to the flare system. In this case the H_2, the emission should be counted in the category "incomplete combustion", while the amount is reduced to unburned gases.			

5.2. H_2 conversion

In the present section, a preliminary list of emissions sources for the archetypes belonging to H_2 conversion is provided in Table 9. As shown, the analysis is limited only to the current mature technologies identified in D1.1:

- Compressors:
  - Reciprocating compressors
  - Centrifugal compressors
  - Diaphragm compressors
- H_2 dispensers
- NH_3 synthesis / cracking
- H_2 liquefaction / regasification

Table 9. Preliminary qualitative list of the emission sources for the archetypes developed in Task 1.1 referred to H_2 conversion.

<table>
<tr><th>Archetype</th><th>Fugitive emissions</th><th>Vented emissions</th><th>Incomplete combustion</th></tr>
<tr><td>Reciprocating compressors</td><td rowspan="6">• Continuous emissions through connection fittings, flanges, valves, etc.
• Continuous emissions due to permeation
.</td><td>• Main Rod Packing – First and second Piston Rod Sealing Gas Vent
• Distance Piece Vent
• Suction Valve Unloader Pneumatic Actuator Rod Packing Sealing</td><td>Not applicable</td></tr>
<tr><td>Centrifugal compressors</td><td>• Compressor Shutdown with Vent
• Seal Gas Filter Cartridge Maintenance</td><td>Not applicable</td></tr>
<tr><td>Diaphragm compressors</td><td></td><td>Not applicable</td></tr>
<tr><td>H_2 dispensers</td><td>• Purging line
• Release of pressure safety valves release[1]
• Break away</td><td>Not applicable</td></tr>
<tr><td>NH_3 synthesis/cracking</td><td>• Start-up operations
• Tank depressurization
• Cracker unit depressurization
• PSA Unit in Cracker Unit</td><td>• Flare Scenario from Compressor
• Flare Scenario from Throttling
• Inert Purge from Refrigeration Unit
• Compressor Seal Gas Losses
• Incomplete Combustion or Combustion Byproducts from Main Cracker Unit</td></tr>
<tr><td>H_2 liquefaction / regasification</td><td>• Inventory Adjustment for Load Control
• Tanks loading procedure</td><td>• Flare Scenario from Liquefaction Unit
• Adsorber Regeneration
• Flare Scenario from Ambient Air Vaporizer
• Boil-Off Gas from Cryogenic Storage Tanks</td></tr>
<tr><td colspan="4">[1] Attention has to be given to avoid double-counting. In some applications, the vents and the discharge of pressure safety valves are directed to the flare system. In this case the H_2, the emission should be counted in the category “incomplete combustion”, while the amount is reduced to unburned gases.</td></tr>
</table>

5.3. H_2 storage

In the present section, a preliminary list of emissions sources for the archetypes belonging to H_2 storage is provided in Table 10. As shown, the analysis is limited only to the current mature technologies identified in D1.1:

- Compressed H_2 tanks
- Liquid H_2 tanks

Table 10. Preliminary qualitative list of the emission sources for the archetypes developed in Task 1.1 referred to H_2 storage.

<table>
<tr><th>Archetype</th><th>Fugitive emissions</th><th>Vented emissions</th><th>Incomplete combustion</th></tr>
<tr><td>Compressed H_2 tanks</td><td>• Continuous emissions through connection fittings, flanges, valves, etc.
• Continuous emissions due to permeation</td><td>• Release of pressure safety valves release[1]
• Tanks purging operation[1]
• H_2 emissions due to embrittlement - Accident</td><td rowspan="2">Only present in case the vented emissions are directed to a flare.</td></tr>
<tr><td>Liquid H_2 tanks</td><td>No relevant differences compared with the emission sources identified for compressed H_2 tanks</td><td>• Release of pressure safety valves release, including boil-off[1,2]
• Tanks purging operation[1]</td></tr>
<tr><td colspan="4">[1] Attention has to be given to avoid double-counting. In some applications, the vents and the discharge of pressure safety valves are directed to the flare system. In this case the H_2, the emission should be counted in the category “incomplete combustion”, while the amount is reduced to unburned gases.
[2] In some cases, as described in D1.1, the boil-off is recovered in the plant by re-liquefaction. In this case, no emission to the atmosphere is expected.</td></tr>
</table>

5.4. H_2 transport

In the present section, a preliminary list of emissions sources for the archetypes belonging to H_2 transport is provided in Table 11. As shown, the analysis is limited only to the current mature technologies identified in D1.1. H_2 transport by ammonia, or other e-fuels carriers is excluded in the current version:

- Transmission and distribution grids
- Compressed H_2 by trucks
- Liquid H_2 by trucks

Table 11. Preliminary qualitative list of the emission sources for the archetypes developed in Task 1.1 referred to H_2 transportation.

<table>
<tr><th>Archetype</th><th>Fugitive emissions</th><th>Vented emissions</th><th>Incomplete combustion</th></tr>
<tr><td>Transmission/distribution grids</td><td>• Continuous emissions through connection fittings, flanges, valves, etc.
• Continuous emissions due to permeation</td><td>• Release of pressure safety valves release[1]
• Purging / venting
• Regular emissions of devices (e.g pneumatic devices)
• Start and stops
• Maintenance vents
• Incidents</td><td>• Turbo-compressor unburned gas in exhaust[2]</td></tr>
<tr><td>Compressed H_2</td><td colspan="3">Refer to compressed H_2 tank archetype.
In addition, loading and unloading ae responsible for emissions</td></tr>
<tr><td>Liquid H_2</td><td colspan="3">Refer to liquid H_2 tank archetype.
In addition, the following should be considered as fugitive emissions:
• Fugitive emissions related to sloshing, flashing phenomena
• Fugitive losses related to thermal stratification and overfill</td></tr>
</table>

[1] Attention has to be given to avoid double-counting. In some applications, the vents and the discharge of pressure safety valves are directed to the flare system. In this case the H_2, the emission should be counted in the category "incomplete combustion", while the amount is reduced to unburned gases.

5.5. H_2 end-uses

In the present section, a preliminary list of emissions sources for the archetypes belonging to H_2 end-uses is provided in Table 11. As shown, the analysis is limited only to the current mature technologies identified in D1.1:

- Refinery
- Nitrogen based fertilizers
- Steel making
- Refuelling stations
- Fuel cells
- Gas turbines
- Heat thermal use

Table 12. Preliminary qualitative list of the emission sources for the archetypes developed in Task 1.1 referred to H_2 end-users.

Archetype	Fugitive emissions	Vented emissions	Incomplete combustion
Refinery	• Continuous emissions through connection fittings, flanges, valves, etc. • Continuous emissions due to permeation	• Release of pressure safety valves release[1] • Start-up	Unburned H_2 in flare or in combustion system
Nitrogen based fertilizers	No relevant differences compared with the emission sources identified for refinery.		
Steel making	No relevant differences compared with the emission sources identified for refinery.		
Refuelling stations	No relevant differences compared with the emission sources identified for refinery	• Release of pressure safety valves release, including boil-off[1,2] • Operational emissions from compression and storages (see the specific archetype)	Not applicable
Fuel cell for mobility (including tank)		• Releases from On Tank Valve (OTV) • The same emissions as for compressed / liquid H_2 tanks	Not applicable
Internal combustion engine (including tank)		• The same emissions as for compressed / liquid H_2 tanks	• Unburned gas in exhaust
Electricity generation – fuel cell		The NHyRA project is aware that more information on other fuel cell plant configurations	SOFC plants: • Unburned gas in exhaust including anode off-gas (if not recycled back in the system)
Gas turbines		• Fuel Gas valve Isolating Interstage Vent • Fuel Gas Valve Isolating Packing vent	• Unburned gas in exhaust
Heat thermal use		• Start and stop	• Unburned gas in exhaust

[1] Attention has to be given to avoid double-counting. In some applications, the vents and the discharge of pressure safety valves are directed to the flare system. In this case the H_2, the emission should be counted in the category "incomplete combustion", while the amount is reduced to unburned gases.

6. Conclusions and recommendations

A preliminary list of emission sources from the equipment in the H_2 value chain has been developed. This list would indicate the NHyRA consortium where values of the emissions are needed to estimate the H_2 emissions in different supply chain scenarios. The literature indicates a limited number of values, and no approach has been agreed, such as for the NG sector. A methodology based on what has already been accepted in the NG sector has been proposed to cover these gaps. More specifically, the definition of the types, categories, and subcategories of the emissions occurring in the archetypes defined in deliverable D1.1 has been described. Furthermore, a preliminary list of the expected emission sources in the value chain has been indicated.

However, some limitations still apply to the present work. First, a limited number of validated data are available. A dedicated methodology to ensure data quality check has been proposed to cover this gap. In fact, despite its complexity, this procedure aims to minimize potential errors and ensure validated data before insertion into the inventory, especially in the case any entity outside the NHyRA Consortium provides them.

Furthermore, a systematic literature review will be put in place in the next months in Task 1.4 to improve the amount of data and contribute to answering the research question, i.e., the estimation of H_2 emissions (Rother, 2007). The literature review will be conducted by NHyRA partners following a rigorous methodology such as, for example, that adopted in the PRISMA methodology (Preferred Reporting Items for Systematic reviews and Meta-Analyses):

- **Identification**. This step consists of identifying the potential documents to be analysed. For this purpose, it is essential to define i) the database where to search documents and ii) the keywords.
- **Screening**. By defining acceptance criteria, the screening evaluates if the documents identified in the previous steps respect the criteria without reading the full text. General criteria are usually applied in this step, such as open access, year of publication, language, publication in peer-reviewed journals, or others. Furthermore, the analysis is limited to the title and the abstract.
- **Eligibility**. By reading the full text, an additional filtering step is performed, removing all the documents that do not fit the research scope or other criteria defined by the reviewers.
- **Inclusion**. After the procedure, only those documents related to the research's purpose are maintained for in-depth analysis.

Since the research topic is quite active nowadays, the process should be periodically performed to include new potential documents for review and additional input data to the inventory.

In addition to the literature review, surveys and interviews should be developed to gather information from stakeholders' experts. Since much of the data refers to experience in the field, there would need to be more than just a literature review. Furthermore, experts' interviews and survey will help to identify the relevant parameters that affect the total emission and that should be recorded in the inventory (if available) to allow further analysis.

7. References

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8. Appendix: the preliminary version of the inventory

The preliminary version of the inventory is reported below. It has to be highlighted that this version is preliminary and it will be updated every six months. Next releases will be in M12, M18, M24, M30 based on the methodology proposed. A final version will be published at M36.

8.1. Relevant parameters

As already indicated, relevant parameters are those factors that could influence the amount of H_2 emission from a specific archetype. Therefore, specific relevant parameters have to be identified for each archetype. Due to the complexity of the analysis, relevant parameters have been identified for electrolysis, liquified H_2 tanks, and standard components like plastic pipes and joints. The list of relevant parameters is shown in Table A.1.

Table A1. Preliminary list of relevant parameters for some of the identified archetypes.

ARCHETYPE	PARAMETER 1	PARAMETER 2	PARAMETER 3	PARAMETER 4	PARAMETER 5	PARAMETER 6
Electrolysis	Technology (AEK/PEM/SOEC/OTHER)	Operative pressure [barg]	Capacity [MW]	Regeneration of the dryer	Service life [years]	-
LH2 Tanks	H2 content [ton] and storage volume (m^3)	Demand profile and application (long term storage / HRS)	Shape	Type of insulation	Service life [years]	Installation (vertical/horizontal), (Above ground/underground)
Pipeline	Wall material	Pressure [barg]	External diameter [mm]	Wall thickness [mm]	Service life [years]	-
Joint	Material	Pressure [barg]	Nominal diameter DN	Type of joint	Service life [years]	-
Further analysis is needed to identify the relevant parameters for the other archetypes.						

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8.2. Cited references in the inventory

	Authors	Title	Year	Link
1	Frazer-Nash Consultancy	Fugitive Hydrogen Emissions in a Future Hydrogen Economy	2022	https://assets.publishing.service.gov.uk/media/624ec79cd3bf7f600d4055d1/fugitive-hydrogen-emissions-future-hydrogen-economy.pdf
2	LINDE	Liquid hydrogen distribution technology	2019	https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf
3	Shoji Kamiya	World's first ocean going liquid hydrogen carrier	2019	https://hysafe.info/wp-content/uploads/sites/3/2021/05/2_1_LH2-carrier-KHI-kamiya-for-publishing-1-1.pdf
4	R. Morales-Ospino, A. Celzard, V. Fierro	Strategies to recover and minimize boil-off losses during liquid hydrogen storage	2023	https://doi.org/10.1016/j.rser.2023.113360
5	R. Valk, R. Hermkens	Leak tightness of PVC fittings with hydrogen	2023	https://www.kiwa.com/4a81a6/globalassets/netherlands/kiwa-technology/downloads/ppxxi-leak-tightness-of-pvc-fittings-with-hydrogen.pdf
6	R. Valk, R. Hermkens	Modern PE pipe enables the transport of hydrogen	2018	https://www.kiwa.com/globalassets/netherlands/kiwa-technology/downloads/hermkens-et-al---pe-pipes-enable-the-transport-of-hydrogen_ppxix_2018-versie-20180710.pdf
7	Arrigoni, A., Bravo Diaz, L.	Hydrogen emissions from a hydrogen economy and their potential global warming impact	2022	https://publications.jrc.ec.europa.eu/repository/handle/JRC130362
8	Cooper, J.; Dubey, L.; Bakkaloglu, S.; Hawkes, A.	Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming	2022	https://www.sciencedirect.com/science/article/pii/S004896972201717X

8.3. H_2 emissions' inventory@v0

The preliminary version of the H_2 emissions is shown in the next page.

Emission inventory	Version n°	0
	Date	31/07/2024
	Authors	NHyRA project

Macro category	Archetype	Type of emission	Category of emission	Sub-Category of emission	Emission equipment - description	Temporal profile of the emission	H2 concentration / Composition of the emission	Relevant parameter n°1	Relevant parameter n°2	Relevant parameter n°3	Relevant parameter n°4	Relevant parameter n°5	Relevant parameter n°6	Data source level	Literature reference	Value of the emission / Emission factor	Unit of measurement	Measurement conditions (if applicable)	Correlations for the estimation of the H2 emission from EF	Notes
Production	Electrolysis	Vented emission	Operations	Starts and stops	Electrolyser	Discontinuous	100%H2	Not declared	Not declared	Not declared	Not declared	-	-	Other estimations	[1]	0.05-0.60	%	Not Applicable	This section will be updated in the next release of the inventory	
Production	Electrolysis	Vented emission	Operations	Regular emissions of devices	Electrolyser	Discontinuous	100%H2	Not declared	Not declared	Not declared	Not declared	-	-	Other estimations	[1]	0.05-0.15	%	Not Applicable		Venting of oxygen (hydrogen crossover)
Production	Electrolysis	Vented emission	Operations	Regular emissions of devices	Temperature / Pressure swing adsorption processes	Continuous	100%H2	Not declared	Not declared	Not declared	Not declared	-	-	Other estimations	[1]	0-10	%	Not Applicable		Purging processes to remove impurities
Production	CH4 Steam reforming	Others (please specify in notes)	All included	All included	Steam methane reforming plant	Continuous & Discontinuous	100%H2							Other estimations	[7]	0,0001	%	Not Applicable		Losses from SMR are currently typically flared, not causing an increase of hydrogen concentration in the atmospher. All emissions type included in the value
Production	Electrolysis	Others (please specify in notes)	All included	All included	Electrolysis plant	Continuous & Discontinuous	100%H2	Not declared	Not declared	Not declared	Not declared			Other estimations	[8]	0.1-4.0	%	Not Applicable		0% losses - alternative fuel used to power the process. No single electrolyser technology is assumed, and the values presented are for a range of electrolysis (alkaline water to biocatalysed)
Production	CH4 Autothermal reforming	Others (please specify in notes)	All included	All included	Blue H2 production plant (from NG)	Continuous & Discontinuous	100%H2							Other estimations	[8]	0,1-1	%	Not Applicable		Values for production of LH2 via ATR (ATR and liquefaction). A disaggregated value was not available. However, it is assumed that value for ATR to explore potential high loss rates as well as to explore loss rates in reforming which are assumed to be similar to electrolysis
Production	Coal gasification	Others (please specify in notes)	All included	All included	Blue H2 production plant (from coal)	Continuous & Discontinuous	100%H2							Other estimations	[8]	0.1-1	%	Not Applicable		All the plant including BOP and all the potential emissions sources are considered
Production	CH4 Steam reforming	Vented emission	Operations	Regular emissions of devices	Temperature / Pressure swing adsorption processes	Continuous	100%H2							Other estimations	[1]	0-10	%	Not Applicable		Purging processes to remove impurities
Conversion	Compression	Others (please specify in notes)	All included	All included	Compressor plant	Continuous & Discontinuous	100%H2							Other estimations	[8]	0.15-0.27	%	Not Applicable		0% losses - alternative fuel used to power the process
Conversion	Liquefaction	Others (please specify in notes)	All included	All included	Liquefaction plant	Continuous & Discontinuous	100%H2							Other estimations	[8]	0.15-2.21	%	Not Applicable		Loss rates differ for liquefaction depending on whether compression occurs in the supply chain. If compression occurs, losses are lower than when liquefying without prior compression.
Conversion	Liquefaction	Others (please specify in notes)	All included	All included	Liquefaction plant	Continuous & Discontinuous	100%H2							Other estimations	[8]	17,43-42,99	%	Not Applicable		Loss rates differ for liquefaction depending on whether compression occurs in the supply chain. If compression occurs, losses are lower than when liquefying without prior compression.
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Not declared	(19000 m3)	Not declared	Spherical	Vacuum insulated	Not declared	Other estimations	[4]	0,06	%/day	Not Applicable		H2 boil off could be recovered through liquefaction (big size application) or burned in a flame producing H2O, reducing the total amount of H2 released to the atmosphere
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Bulk storage	(2500 m3)	Not declared	Spherical	Vacuum perlite insulation	Above ground	Other estimations	[3]	< 0.1	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Bulk storage	145 ton (2300 m3)	Not declared	Spherical	Not declared	Not declared	Other estimations	[2]	< 0.1	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Bulk storage	70.2 ton (1100 m3)	Not declared	Spherical	Not declared	Above ground / Vertical	Other estimations	[2]	< 0.1	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Bulk storage	19.3 ton (300 m3)	Not declared	Cylindrical	Not declared	Above ground / Horizontal	Other estimations	[2]	0,3	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Not declared	(100 m3)	Not declared	Spherical	Vacuum insulated	Not declared	Other estimations	[4]	0,2	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Other applications	4.6 ton (71 m3)	High demand	Cylindrical	Vacuum perlite	Above ground / Vertical	Other estimations	[2]	< 0.9	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Not declared	(50 m3)	Not declared	Spherical	Vacuum insulated	Not declared	Other estimations	[4]	0.3-0.5	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Other applications	0.4 ton (6 m3)	Low demand	Cylindrical	Special insulation material inside vacuum space	Above ground / Vertical	Other estimations	[2]	> 0.5	%/day	Not Applicable		
Storage	LH2 Tanks	Vented emission	Operations	Evaporation - Boil off	Tank	Discontinuous	100%H2	Other applications	0.9 ton (11.5 m3)	Low-medium demand	Cylindrical	Multilayer insulation inside vacuum space	Above ground / Horizontal	Other estimations	[2]	< 0.6	%/day	Not Applicable		
Transport	Transmission & Distribution grid	Fugitive emission	All included	All included	Transmission system	Continuous & Discontinuous	100%H2	Not declared	Not declared	Not declared	Not declared	Not declared	Not declared	Other estimations	[1]	0.02-0.04	%/year	Not Applicable		Values derived from NG leakage.
Transport	Transmission & Distribution grid	Fugitive emission	All included	All included	Distribution system	Continuous & Discontinuous	100%H2	Not declared	Not declared	Not declared	Not declared	Not declared	Not declared	Other estimations	[1]	0.1-0.23	%/year	Not Applicable		Values derived from NG leakage.
Transport												Not declared								
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PVC-U	200 mbarg	111,08	3,02	Not declared	53	Experimental values reported in the literature	[4]	90,9	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PVC-U	200 mbarg	110,23	3,44	Not declared	46	Experimental values reported in the literature	[4]	87,3	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PVC-U	200 mbarg	110,3	2,94	Not declared	14	Experimental values reported in the literature	[4]	115,3	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PVC-Hi	200 mbarg	110,43	2,95	Not declared	27	Experimental values reported in the literature	[4]	117,2	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PVC-Hi	200 mbarg	110,38	3,08	Not declared	7	Experimental values reported in the literature	[4]	181,3	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PVC-Hi	200 mbarg	110,45	2,99	Not declared	27	Experimental values reported in the literature	[4]	113,3	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		
Transport	Pipeline	Fugitive emission	Leaks due to connections/loss of tightness	Leaks typically due to gradual changes in conditions	Plastic joint	Continuous	100%H2	PVC-U	200 mbarg	110	Not declared	Not declared	Straight joint	Experimental values reported in the literature	[4]	6,5	ml/day	Measured with the following instrumentations: gas chromatograph		Aged at 60°C for 1000 hours in H2 at 30 mbarg (equivalent to 50 years of operation) before testing
Transport	Pipeline	Fugitive emission	Leaks due to connections/loss of tightness	Leaks typically due to gradual changes in conditions	Plastic joint	Continuous	100%H2	PVC-U	200 mbarg	110	56	Not declared	Straight joint	Experimental values reported in the literature	[4]	7.5	ml/day	Measured with the following instrumentations: gas chromatograph		Aged at 60°C for 1000 hours in H2 at 30 mbarg (equivalent to 50 years of operation) before testing
Transport	Pipeline	Fugitive emission	Leaks due to connections/loss of tightness	Leaks typically due to gradual changes in conditions	Plastic joint	Continuous	100%H2	PVC-Hi	200 mbarg	110	42	Not declared	Straight joint	Experimental values reported in the literature	[4]	7.3	ml/day	Measured with the following instrumentations: gas chromatograph		Aged at 60°C for 1000 hours in H2 at 30 mbarg (equivalent to 50 years of operation) before testing
Transport	Pipeline	Fugitive emission	Leaks due to connections/loss of tightness	Leaks typically due to gradual changes in conditions	Plastic joint	Continuous	100%H2	PVC-Hi	200 mbarg	110	31	Not declared	Straight joint	Experimental values reported in the literature	[4]	7.4	ml/day	Measured with the following instrumentations: gas chromatograph		Aged at 60°C for 1000 hours in H2 at 30 mbarg (equivalent to 50 years of operation) before testing
Transport	Pipeline	Fugitive emission	Permeation	Wall permation	Plastic pipe wall	Continuous	100%H2	PE100-RC	2 barg	110	6,3	Not declared	Not declared	Experimental values reported in the literature	[5]	126,8	(ml x mm) / (m2 x day x bara)	Measured with the following instrumentations: gas chromatograph		Experiment performed at room temperature
Transport	CH2 Tanks	Others (please specify in notes)	All included	All included	Supply chain	Continuous & Discontinuous	100%H2							Other estimations	[7]	1	%/tonH2	Not Applicable		These losses are mainly linked to the purging of the trailer hose, and to leakages from fittings and valves
Transport	LH2 Tanks	Others (please specify in notes)	All included	All included	Supply chain	Continuous & Discontinuous	100%H2							Other estimations	[7]	10 (2 at 2030)	%/tonH2	Not Applicable		Mainly due to liquefaction process and the boil-off during transfer operations
Transport	Pipeline	Others (please specify in notes)	All included	All included	Supply chain	Continuous & Discontinuous	100%H2							Other estimations	[7]	1 (0.7 at 2030)	%	Measured with the following instrumentations: gas chromatograph		
Transport	Transmission & Distribution grid	Others (please specify in notes)	All included	All included	All transmission system included	Continuous & Discontinuous	100%H2							Other estimations	[8]	0,84-1,58	%	Not Applicable		All the emission sources are considered
Transport	Transmission & Distribution grid	Others (please specify in notes)	All included	All included	All transmission system included	Continuous & Discontinuous	100%H2							Other estimations	[8]	1,67-3,12	%	Not Applicable		All the emission sources are considered
Transport	Transmission & Distribution grid	Others (please specify in notes)	All included	All included	All distribution system included	Continuous & Discontinuous	100%H2							Other estimations	[8]	0,46-0,92	%	Not Applicable		All the emission sources are considered
Transport	Transmission & Distribution grid	Others (please specify in notes)	All included	All included	All distribution system included	Continuous & Discontinuous	100%H2							Other estimations	[8]	0,17-0,44	%	Not Applicable		All the emission sources are considered
Transport	Transmission & Distribution grid	Others (please specify in notes)	All included	All included	All distribution system included	Continuous & Discontinuous	100%H2							Other estimations	[8]	0,02-0,14	%	Not Applicable		All the emission sources are considered
End-uses	HRS - gas delivery	Others (please specify in notes)	All included	All included	Supply chain	Continuous & Discontinuous	100%H2							Other estimations	[7]	3 (2 at 2030)	%/tonH2	Not Applicable		
End-uses	HRS - liquid delivery	Others (please specify in notes)	All included	All included	Supply chain	Continuous & Discontinuous	100%H2							Other estimations	[7]	8.5 (2 at 2030)	%/tonH2	Not Applicable		